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The Effects of Different Rates of Ascent on the Incidence of Altitude Decompression Sickness

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ABSTRACT

The effect of different rates of ascent on the incidence of altitude decompression sickness (DCS) was analyzed by a retrospective study on 14,123 manflights involving direct ascent up to a 38,000-foot altitude. The data were classified on the basis of altitude attained, denitrogenation at ground level, duration of stay at altitude, rest or exercise while at altitude, frequency of exercise at altitude, and ascent rates. This database was further divided on the basis of ascent rates into different groups from 1000 ft/min up to 53,000 ft/min. The database was analyzed using multiple correlation and regression methods, and the results of the analysis reveal that ascent rates influence the incidence of DCS in combination with the various factors mentioned above. Rate of ascent was not a significant predictor of DCS and showed a low, but significant multiple correlation ($R=0.31$) with the above factors. Further, the effects of rates below 2500 ft/min are significantly different from that of rates above 2500 ft/min on the incidence of symptoms ($P=0.03$) and forced descent ($P=0.01$). At rates above 2500 ft/min and up to 53,000 ft/min, the effects of ascent rates are not significantly different ($P>0.05$) in the population examined while the effects of rates below 2500 ft/min are not clear.

INTRODUCTION

GENERAL

Whenever there is acute reduction in ambient pressure, body tissues are susceptible to a series of pathophysiological changes resulting in a syndrome called decompression sickness (DCS). This condition is primarily due to the supersaturation of body tissues with inert gas, especially nitrogen, leading to the formation and growth of gas bubbles in both intravascular and extravascular tissues. The presence of these bubbles are thought to induce the symptoms of DCS through mechanisms involving pressure and/or occlusion in the tissues (1,31,32,66). In space activities, altitude DCS is a real possibility when the astronauts leave the normobaric environment of the current spacecraft in a hypobaric space suit in preparation for extravehicular activities.

DCS is influenced by various individual and environmental factors and excellent reviews on this subject are available (1,31,32,41). However, the effect of certain variables like rate of change of pressure is not yet clear and studies examining this aspect have been few (6,8,45). Most of the observations on rate of change of pressure have been obtained from studies examining other aspects of DCS or during operational studies (15,46). In the absence of specific information, it is difficult to draw definite conclusions on the effect of these experimental variables on DCS.

BACKGROUND OF THE STUDY

The influence of different rates of ascent (ROA) on the incidence of altitude DCS is of operational importance in prescribing optimal ascent rates for various missions. Hypobaric chamber studies, including those by NASA and the USAF simulating extravehicular activities, have used ROA of 3000 ft/min or 5000 ft/min in most of these experiments. However, in operational decompressions of the shuttle airlock, rates up to 6500 ft/min are encountered due to the characteristics of the airlock and purge characteristics of the suit (13). It is not known whether such differences between experimental and operational rates influence the outcome of decompression differently.

Though many investigators are of the opinion that high ascent rates increase the symptoms of DCS (1,40,66), there is little experimental support for this belief. Some studies found no significant increase in the incidence of DCS when two different ROA were compared (14,20,53). Several authorities on decompression have stated the opinion that ROA is not a significant factor under operational circumstances (31,61). While this may be generally accepted, lack of data on certain ascent rates leaves no room to draw conclusions when specific operational problems are encountered. Hence, there is a need to examine the influence of different ROA on the incidence of DCS.

OBJECTIVES

Though it is believed that rate of ascent may exert an effect on the incidence of DCS, it is not considered to be a primary factor like altitude or denitrogenation in influencing the outcome (38,65,66). Since any study designed to evaluate the effect of ROA at different rates to various altitudes would be very exhaustive, we considered it prudent to examine the vast body of literature on DCS in an attempt to single out the effect of ascent rates on DCS. The available literature on DCS is very extensive and heterogenous. Though DCS in general is influenced by a variety of factors, the effect of ROA is possibly secondary to certain critical factors like altitude attained, denitrogenation, tissue ratio, and exercise performed at altitude. At the same time, it is difficult to obtain experimentally controlled parameters at different ROA. Hence, this study was initiated with the following objectives:

1. To review the literature specifically addressing the effects of different ascent rates on altitude decompression sickness

2. To collect and classify data on altitude decompression sickness from the available literature with respect to various ascent rates

3. To examine the effect of different ascent rates on altitude decompression sickness by means of appropriate statistical procedures

REVIEW OF THE LITERATURE

EARLY EXPERIMENTAL EVIDENCE

Investigators of altitude DCS have long been interested to know the influence of different ascent rates on the symptoms. There are numerous observations and critical statements, but little experimental evidence to indicate any cause and effect relationship. A definitive experiment to find the effect of rate of ascent was first conducted by Armstrong and Heim on rabbits. They found that at rates of 100 ft/min, the animals tolerated altitudes around 31,000 ft and at 10,000 ft/min, they tolerated up to 40,000 ft. This study emphasized the effects of hypoxia rather than DCS with respect to altitude tolerance. However, they observed that ascent rates could influence altitude tolerance and therefore should be specified before comparing different studies. They also concluded that the low tolerance associated with the low ROA in their study was due to the degree and duration of anoxemia rather than the altitude attained (6).

Haldane et.al., in their classic paper had earlier reported that a decompression ratio of 2:1 would be safe in divers and produce no symptoms of DCS (11). This principle was tested in animal experiments by Daly et.al., using various ascent rates under hyperbaric and hypobaric exposures, and they found that extrapolation of Haldane's safe decompression rates were not necessarily applicable to hypobaric exposures (19). Status report in a Flying Personnel Research Committee memorandum of that time also indicated that there was no safe and experimentally proven minimum rates available for hypobaric exposures (4). However, it was generally opined by various investigators that ROA might influence DCS by way of nitrogen elimination (8,10,19,30,38,47,58). Thus, rapid rates of ascent would allow less time for nitrogen elimination and increase the incidence, while slow rates would permit more denitrogenation and reduce the incidence.

Significant contribution to the preventive role of denitrogenation on DCS was provided by Behnke in 1935. He showed that elimination of nitrogen is exponential with 75 percent of the gas being eliminated at a comparatively rapid rate in the first 60 minutes of denitrogenation and formulated the nitrogen elimination curve. He showed that incidence of DCS is reduced when more nitrogen is eliminated from the body (7). In another experiment Benhke et.al., exposed divers to various altitudes at 5000 ft/min (they called this rate "rapid") ROA and found that up to a 20,000 ft altitude, no definitive symptoms of DCS occurred. They defined this altitude as the "threshold" for manifest bubble formation. They opined that the effect of different ascent rates would be different below and above this threshold (8,9). They also thought that denitrogenation occurred during ascent and was responsible for the reduction in symptoms with ascent on oxygen.

Experiments by Gray established that denitrogenation during ascent was feasible and he reported that breathing pure oxygen at altitudes up to 20,000 ft was as effective as ground level denitrogenation (36,38). Similar findings were also reported by Canadian investigators (30). Henry reported that the incidence of DCS was 72 percent in men undertaking simulated "fighter" ascents to an altitude of 35,000 ft (at 3000 ft/min) while it was 60 percent in men undertaking "bomber" type ascents (at 1000 ft/min up to a 25,000-ft

altitude and later at 400 ft/min to 35,000 ft). He found no striking difference between these two ascent rates (43).

German experience during World War II showed that at nominal ascent rates (4000 ft/min) DCS was seen in approximately 10 percent of subjects participating in training flights to an altitude of 40,000 ft, while it was 60 percent when rapid rates (40,000 ft/min) were employed. These investigators found that the period of denitrogenation was a crucial factor in determining the outcome of DCS (46).

Canadian investigators, especially Fraser, have commented on the effect of ROA on DCS. In decompressions involving ascent rates of 2300 ft/min and 600 ft/min to 35,000 ft, Fraser found no difference in the incidence of symptoms (30). Evelyn's work involving ascent rates from 500 ft/min to 4000 ft/min also showed no detectable difference in the incidence of bends within the group (30).

Griffins et.al., examined the effect of ascent rates in subjects exposed to an altitude of 35,000 ft and found that rapid ascent rate (5000 ft/min) significantly increased the symptom scores compared to the lower ROA (1000 ft/min). They further found that preoxygenation had no significant influence on the symptoms at the rapid ascent rate (40). This study is often quoted by those supporting the concept of higher ROA increasing the incidence of DCS, and this is possibly the only controlled study which shows such an effect. However, there are some limitations in interpreting their results because the study also investigated several other variables such as lower ambient temperatures (20 to 30 degrees Fahrenheit) and a combination of light (cold) and electrically heated (warm) clothing. Though they differentiated between the two ascent rates in this test, they did not isolate the effect of clothing. Further, they analyzed their results in terms of a symptom score - not a well accepted or validated method for analyzing the outcome of DCS. Their results on the influence of ascent rates thus are not isolated from the effects of clothing and their statistical treatment of data in terms of symptom scores is open to question.

Clarke et.al., employed essentially the same ROA (1300 ft/min and 5000 ft/min) used by Griffins et.al., in flights to 38,000 ft lasting approximately 130 minutes with the slow ascent and 100 minutes with the rapid ascent, but with exercise at altitude. They found forced descents of 89 percent, 84 percent, and 71 percent with slow ascent, and 94 percent and 98 percent with rapid ascent in their subjects with no prior denitrogenation (14).

EVIDENCE FROM RAPID DECOMPRESSION STUDIES

Hitchcock conducted a series of experiments to identify the effect of different ascent rates on incidence of symptoms in rapidly decompressed subjects (45). He employed control ascent rates of 3000 ft/min and rapid rates varying from 9800 ft/min up to 25,000 ft/min for decompression of subjects from altitudes of 20,000 ft to 40,000 ft with exercise at altitude. The amount of denitrogenation possible in the control runs was compensated in the explosive runs by breathing oxygen for an equivalent period prior to decompression. He found that though there was an increase in the incidence of bends with rapid ascent rates, this effect was minimal when subjects did not

denitrogenate (on automix), and there was no significant differences among the different rapid ROA employed in the study. He concluded that though rapid ROA increased the susceptibility to DCS, this "increase is so slight as to be almost negligible" (45).

Based on available evidence on the threshold of occurrence and incidence of DCS, Nims opined that the effect of ROA may be different at altitudes below and above 16,000 ft. Below 16,000 ft, he considered only denitrogenation to be possible while above 16,000 ft, he considered bubble formation to be extremely probable (58). However, the effects of altitude, denitrogenation, and rate of ascent were considered to be closely interrelated by all of these investigators.

EVIDENCE FROM EXTRAVEHICULAR STUDIES

Several experiments conducted by NASA and the USAF have mostly been tailored to study the requirements for extravehicular activity in space missions (3,15,20,21,23,24,48,49,52,63,67). These studies were designed to verify operational protocols or to identify protocols that would produce a minimum of symptoms and bubbles. These studies employed hypobaric exposures simulating space suit pressures for periods varying from 6 hours and up to 24 hours at altitude. Hence, denitrogenation in these studies were often carried out for prolonged periods of time and occurrence of symptoms and forced descent were defined very strictly. Initial studies conducted up to the early 1970's employed higher rates of ascent ranging from 8800 ft/min to 52,500 ft/min (2,20,21,52,53). These studies also involved exposure to mixed gas atmospheres and staged decompression procedures. In one of these studies, Damato et.al., compared these ROA and found no major difference in the incidence of DCS amongst them (20).

Later studies on extravehicular activity employed uniform ROA of 5000 ft/min or 3000 ft/min (15). Studies were also conducted at altitudes below 30,000 ft with and without denitrogenation, and they all involved exposures to mixed gas environments. Rate of ascent was considered only as a secondary factor in these studies.

MATERIALS AND METHODS

DATA COLLECTION

The required data were collected mainly from two sources - those available in the open literature and other unpublished military and scientific reports on DCS. Most of the unpublished reports were kindly provided by the National Research Council Reference Library at Washington, D.C. and the USAF School of Aerospace Medicine at Brooks Air Force Base, Texas.

The following criteria were applied in collecting and compiling the data:

1. Only studies involving ascent to altitudes up to 38,000 ft were collected.

2. Studies involving stay for any period of time at intermediary altitudes were not included.

3. Studies employing no prior denitrogenation and those with only ground level denitrogenation were included. However, studies using oxygen or air and oxygen mixture during the period of ascent were also included. Studies employing pressure breathing were excluded.

4. Studies involving rest or exercise at altitude were included and those with exercise at any other period of decompression were excluded (e.g., exercise during denitrogenation).

5. Incidence of symptoms was defined as the presence of any of the symptoms of DCS, including bends, chokes, gas pains, and other neurocirculatory manifestations, where separately mentioned. No grading of symptoms was attempted.

6. Forced descent was defined as the occurrence of descent due to any criterion whether subjective or experimentally defined in the study - indicating failure to remain at altitude.

The collected data were divided into two major groups - those wherein the subjects either exercised or rested at altitude. They were further subdivided into those with and without ground level denitrogenation. Tissue ratio (TR) for each case was determined using the procedure adopted by NASA for defining risk of DCS associated with aerospace activities (15). This procedure uses a single critical tissue with 360-minute half-time for calculating TR and is summarized in appendix A. The time taken to reach the required altitude and pure oxygen breathed during this period of time was also included in arriving at the TR on reaching the altitude. However, no such inclusion was possible in cases where breathing oxygen/air mixtures occurred during ascent.

The collected data were classified for each experiment on the basis of altitude attained, TR, denitrogenation, duration of stay at altitude, exercise or rest at altitude, frequency of exercise per hour, rate of ascent, and incidence of symptoms and forced descent (appendix B). Rate of ascent was calculated in each experiment from the time taken to reach the altitude from ground level. Period of stay at altitude was the experimentally specified duration, since mean duration of stay was not available for each of the individual experiments examined in this report. Exercise frequency was taken as the number of cycles of the particular exercise regimen carried out during an hour of stay at altitude. For example, five knee bends and five push-ups undertaken every 3 minutes would constitute an exercise frequency of 20 cycles per hour. From an examination of the data on ROA, it was found that grouping of ROA based on the most commonly employed ascent rates would provide valuable information. Though individual ascent rates are mentioned in figures in this report, they always included the ROA for the particular group. Since there were no data on ascent rates from 5500 ft/min up to 8500 ft/min, the ascent rates were grouped as follows:

1. Below 2500 ft/min (primarily included ROA of 1000 ft/min)

2. From 2501 ft/min to 3500 ft/min (primarily 3000 ft/min)

3. From 3501 ft/min to 5500 ft/min (primarily 5000 ft/min)

4. From 5501 ft/min to 10,500 ft/min

5. From 10,501 ft/min to 20,500 ft/min

6. Above 20,501 ft/min

ANALYSIS OF DATA

The database was analyzed on the basis of the classification described above and given in appendix B. To make optimum utilization of all the available data, those not reported in the individual studies were considered as missing and statistical corrections were made (25). This approach was considered appropriate since there were many unreported data in the compiled database. The data were then examined using a computerized multiple correlation and regression program (25). The regression models used in this report for the analysis of data are as follows:

1. All experimental data

Symptoms = b_0 + b_1 (altitude) + b_2 (duration of stay) + b_3 (period of denitrogenation) + b_4 (frequency of exercise) + b_5 (rate of ascent) + e_1.
The same model was used for predicting forced descent.

2. Resting subjects

Symptoms = b_0 + b_1 (altitude) + b_2 (period of denitrogenation) + b_3 (rate of ascent) + e_1.
The same model was used for predicting forced descent. The correlation matrix was not positive semi-definite for purposes of statistical analysis with the inclusion of data on duration of stay at altitude and was therefore excluded from this model.

3. No prior denitrogenation and rest at altitude

Symptoms = b_0 + b_1 (altitude) + b_2 (rate of ascent) + e_1.
The same model was used for predicting forced descent. Duration of stay at altitude was not included for the reasons stated in model b.

4. Exercising subjects

Symptoms = b_0 + b_1 (altitude) + b_2 (duration of stay) + b_3 (period of denitrogenation) + b_4 (frequency of exercise) + b_5 (rate of ascent) + e_1.
The same model was used for predicting forced descent.

5. No prior denitrogenation and exercise at altitude

Symptoms = b_0 + b_1 (altitude) + b_2 (duration of stay) + b_3 (frequency of exercise) + b_4 (rate of ascent) + e_1.
The same model was used for predicting forced descent.

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6. Prior denitrogenation and exercise at altitude

Symptoms = b0 + b1 (altitude) + b2 (duration of stay) + b3 (period of denitrogenation) + b4 (frequency of exercise) + b5 (rate of ascent) + e1. The same model was used for predicting forced descent.

In these models, b0 is the intercept, b1, b2, b3, b4, and b5 are the regression coefficients and e1 is the error factor.

Further, the effect of different ascent rates on symptoms and forced descent was tested for homogeneity of data using Mann-Whitney's "U" statistic or Kruskal-Wallis one-way analysis of variance (62), where appropriate. These statistical tests were carried out in the facility's DEC VAX 11/780 computer system through the BMDP statistical software package (25). For all statistical tests, the level of significance was chosen as p equal to or less than 0.05.

RESULTS

A total of 150 individual experiments from 42 reports and involving 14,123 man-flights were examined in this study. The number of man-flights examined in resting and exercising subjects is given in table 1, and the number of man-flights examined under different ascent rates is given in table 2. The multiple correlation coefficients of ROA with the other independent variables along with the correlation of these independent factors on the incidence of symptoms and forced descent (dependent variables) for the 150 experimental data are given in table 3 and separately for resting and exercising subjects in tables 4 and 5, respectively.

The regression coefficients of ROA for predicting the outcome of DCS in the presence of other independent factors and their statistical significance are given in tables 3, 6, and 7. Results of the tests of independence for the various ROA and their statistical significance are given in tables 8 through 13.

The results of the multiple correlation and regression were analyzed with particular reference to the influence of ascent rates on DCS. The influence of other experimental parameters on DCS will not be elaborated in this report and will be discussed separately in another report.

Rate of ascent showed significant influence on other independent variables examined in this study in all 150 experiments combined and in those involving resting or exercising subjects taken separately. The combination of these independent factors also significantly influenced the incidence of symptoms and forced descent (tables 3,4,5).

However, rate of ascent was not a significant predictor of the incidence of symptoms and forced descent under the above experimental conditions (tables 3,6,7).

Tests of independence showed that the incidence of symptoms and forced descent in the various ROA groups were significantly different in the com-

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bined database and in those involving resting or exercising subjects taken separately (tables 8,9,10). However, above an ROA of 2500 ft/min and up to 53,000 ft/min, the data were homogenous with respect to the incidence of symptoms and forced descent. Further breakdown of data based on resting and exercising subjects was also done and is discussed in the appropriate sections below.

DISCUSSION

It has been observed earlier that any influence of ROA on DCS is possibly due to its interaction with the various independent factors like altitude, denitrogenation, and tissue ratio. DCS is influenced further by the presence or absence of exercise at altitude (12,16,27,29,37,39,42). From the results of the analysis, it is necessary to evaluate the relationship of these independent factors separately on ROA and their combined effect on the outcome of DCS.

INFLUENCE OF ALTITUDE

General

It is known that the incidence of DCS increases as the altitude increases. The effect of higher altitudes is to increase the incidence of DCS and hasten the onset of symptoms (1,31). This effect of altitude is evident in all these studies employing various rates of ascent (appendix B).

Though rate of ascent shows a low multiple correlation (R=0.32) with other independent factors such as altitude, denitrogenation, duration of stay at altitude, and exercise frequency, it is not a significant predictor of either the symptoms (P=0.26) or forced descent (P=0.40) in the population examined (table 3). To obtain more information on the combined effects of denitrogenation and exercise on ROA the data were examined further as discussed below.

The data on nondenitrogenated subjects in terms of the incidence of symptoms and forced descent are given in figure 1 for resting subjects and figure 2 for subjects exercising at altitude. In subjects resting at altitude, there is a high correlation with the linear fit of data as given by the coefficient of determination (squared R) accounting for as much as 79 percent and 73 percent of the variance in the incidence of symptoms and forced descent, respectively (fig.1).

The incidence of symptoms also gives a high correlation with the linear fit of data in exercising subjects (squared R=0.76) though it is much less (squared R=0.57) in the case of forced descent (fig.2). This is probably due to the different criteria used for defining forced descent in these studies. Further examination of data with respect to ascent rates at 3000 ft/min and 5000 ft/min in the above experiments is given in figures 3 and 4, respectively, and shows limited data at these rates in resting subjects. Data on denitrogenated subjects under these ascent rates were not examined separately as they involved various periods of denitrogenation.

Threshold Altitude of DCS

The effect of altitude is further compounded by the fact that the probability of DCS is more after a certain "threshold" altitude (8,58). Most experimenters believe that this threshold altitude lies at approximately 18,000 ft (31,41,61). Hence, earlier workers thought that the influence of ROA was likely to be different below and above this threshold altitude (45). It is very difficult to substantiate these observations, though it is generally known that the probability of DCS greatly increases above a threshold altitude (1,30,31,41).

Recently, operational utility of the concept of a threshold limit for DCS has been questioned. Much evidence has been put together to demonstrate that for any particular situation, the altitudes at which the probability of incidence of symptoms is less than 0.05 is a more useful reference than threshold altitude (50). Kumar and Waligora have shown that these "critical altitudes" in nondenitrogenated subjects resting for short periods (< 45 minutes) is probably in the range of 25,000 ft to 30,000 ft and in the range of 11,000 ft to 17,000 ft in subjects exercising at altitude for up to 6 hours. An examination of figures 1 and 2 are in general agreement with these observations. In light of the above, no possible effect of ROA on threshold altitude could be determined in this study.

INFLUENCE OF DENITROGENATION

Extensive work has been done to demonstrate the protective influence of ground level denitrogenation on the incidence of DCS (9,10,17,28,34,44,47). This effect is dependent on the period for which denitrogenation is carried out. Thus, in experiments involving extravehicular activity, Waligora et.al., have shown that as much as 8 hours of denitrogenation is required to ensure nonoccurrence of DCS at 30,000 ft (67). Duration of denitrogenation examined in this review varied from 15 minutes up to 8 hours for exposures to various altitudes (appendix B).

Mechanism of Interaction

Rate of ascent may influence DCS through denitrogenation (7,47). Earlier experiments by Behnke suggested that denitrogenation might occur during the period of ascent (8). Following this lead, Gray found that even 15 minutes of ground level denitrogenation offered sufficient protection for a 2-hour exposure to 38,000 ft at an ascent rate of 4000 ft/min in subjects resting at altitude (36). The low occurrence of DCS in such a case was taken as evidence of denitrogenation occurring during the period of ascent. In another study he found that the effectiveness of breathing pure oxygen for any amount of time decreased at altitudes above 20,000 ft while compared to denitrogenation carried out at ground level (38). He further opined that useful denitrogenation could be achieved in flight if carried out below 20,000 ft. Thus, a low rate of ascent would provide more time for denitrogenation under these circumstances and denitrogenation for any amount of time was considered beneficial.

Experiments by Marbarger et.al., showed that with 2 hours of denitrogenation the amount of nitrogen eliminated was 77 percent at 8000 ft, 71 percent at 12,000 ft, 64 percent at 18,000 ft, and 61 percent at 22,000 ft while com-

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pared to the same duration of ground level denitrogenation (exposure was to 38,000 ft at an ascent rate of 3000 ft/min) (54). Jones found that denitrogenation carried out at altitudes below 20,000 ft did not strictly add on to the general preoxygenation time and between 20,000 ft to 30,000 ft was only 3/4 to 1/2 as effective as ground level denitrogenation (47).

It appears from these that though denitrogenation is possible during ascent, the amount of denitrogenation achieved during such a period and its effectiveness are variable. Further, these observations apply only to subjects resting at altitude. The protective effect of denitrogenation is limited if exercise is carried out at altitude (44,47).

Influence of Denitrogenation

In subjects resting at altitude with no prior denitrogenation, ROA is not a significant predictor of the incidence of DCS (table 6). Similarly, in subjects with no denitrogenation and exercising at altitude, ROA is not a significant predictor of DCS. Only in the case of denitrogenated subjects exercising at altitude, ROA is a significant predictor of forced descent (P=0.006) (table 7).

Tests of independence of all ROA groups on the outcome of DCS shows homogeneity of data without denitrogenation in exercising subjects (table 11) while it is heterogenous without denitrogenation in resting subjects (table 11) and with denitrogenation in exercising subjects (table 12). This would show complex interaction of ROA with denitrogenation and exercise. Further, these results need cautious interpretation since statistical tests of independence test only the null hypothesis for independence of different groups and do not show causal effects (62).

To illustrate the influence of different ROA on the incidence of DCS, we examined altitudes of 35,000 ft and 38,000 ft individually in our study. This examination was possible only in exercising and not in resting subjects due to limited data on these subjects.

Influence of ROA and Denitrogenation at 35,000 Ft

With no denitrogenation, the incidence of symptoms are higher at ROA of 5000 ft/min and less at 3000 ft/min in subjects exercising at an altitude of 35,000 ft. There is an inverse relationship with increasing period of denitrogenation. This has a correlation of r = 0.87 at the higher and r = 0.90 at the lower rates with the linear fit (fig. 5). A similar relationship is also evident with the incidence of forced descent (fig. 6). However, tests of independence showed homogeneity of data (table 13) suggesting similar influences of these two rates of ascent under various periods of denitrogenation.

Influence of ROA and Denitrogenation at 38,000 Ft

Due to a paucity of experimental data, ROA of 1000 ft/min and 5000 ft/min were compared at an altitude of 38,000 ft and the results are represented in figures 7 and 8. It is interesting to note that both the incidence of symptoms and forced descent are higher with the 1000 ft/min ascent rate. The inverse relationship is again evident here with an increasing period of

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denitrogenation. However, here again with varying periods of denitrogenation these ascent rates do not differently influence the outcome of DCS (table 13).

Thus, it appears that in exercising subjects, the influence of these ROA are not significantly different on the outcome of DCS under various levels of denitrogenation.

TISSUE RATIO CONCEPT

The cases examined in this study have included different altitudes and pre-breathe periods. It is, however, possible to use much of this data by utilizing the unifying concept of tissue ratio. This takes into consideration altitude attained and prior ground level denitrogenation. Hence, we first examined the relationship of TR with the symptoms and forced descent in DCS. As explained in appendix A, the 360-minute half-time tissue was taken as the reference. This was calculated using the same program being used by this laboratory to calculate TR for evaluating the effectiveness of operational DCS prevention protocols (15).

In resting subjects, we found a correlation of $r = 0.70$ and $r = 0.73$ for the incidence of symptoms and forced descent, respectively, with TR in the linear fit of data as seen in figure 9. This correlation is not improved further by fitting exponential or polynomial models. The experimental data are limited in the case of resting subjects and preclude any further observations.

In the case of subjects exercising at altitude, the linear relationship of TR has a higher correlation of $r = 0.81$ with symptoms and $r = 0.78$ with forced descent as seen in figures 10 and 11. Once again, exponential or polynomial models do not offer further improvement in correlation. It must be noted here that these data include ascent rates ranging from 1000 ft/min up to 60,000 ft/min, although the majority of the man-flights were conducted at the modest rates of 3000 ft/min to 5000 ft/min (table 2).

Calculation of TR including time taken to reach altitude (and therefore denitrogenation) with the period of ground level denitrogenation showed very little changes in TR calculated without such additional time indicating that denitrogenation achieved during this period would be very little. Further, use of TR has the advantage of comparing all data together and enables combination of the effects of altitude and denitrogenation. Hence, further analysis of our database was done in terms of TR to identify the effect of ROA on the incidence of DCS.

INFLUENCE OF EXERCISE

Exercise at altitude increases the incidence of DCS. This effect is presumably produced by facilitation of bubble formation by the increased presence of carbon dioxide in working muscles and by tribonucleation in closely approximated tight tissues such as tendons and bones (41). Hence, the effect of ROA on DCS is further masked by exercise undertaken at altitude.

In our analysis, the incidence of symptoms (P=0.01) and forced descent (P=0.007) are significantly different between resting and exercising subjects

(table 13). Figures 12 and 13 compare the effect of 3000 ft/min and 5000 ft/min ROA separately in resting and exercising subjects. At 3000 ft/min, the outcome of DCS is significantly different between resting and exercising subjects under various TR. Similar differences were observed only with the incidence of symptoms and not forced descent at ascent rate of 5000 ft/min (table 13).

These results would indicate that under similar ascent rates, the effects of exercise and rest at altitude are significantly different from each other in influencing the incidence of DCS.

EFFECT OF VARIOUS RATES OF ASCENT

Statistical Limitations

Analysis of our database reveals that ROA does not directly increase the symptoms of DCS. Their effects, if any, appear to be due to the interaction of altitude, denitrogenation, and exercise or rest at altitude. Multiple correlation analysis is the best tool available to segregate the effects of these various factors on one another. However, assumption of a linear relationship implies a normal distribution of the observations and reduction of the squared residuals to a minimum (26). Many statisticians place primary importance upon regression rather than correlation since the interpretation of the regression coefficient is the same regardless of whether the values are drawn at random or purposely selected (26). In spite of this limitation, many of the relationships examined in this analysis show a high correlation with the linear fit and exponential or polynomial models offer little advantage over this.

In analyzing the results from multiple correlation and regression analysis, squared multiple correlation and standard error of the estimate offer important information. The squared R is called the coefficient of determination if the dependent variable is causally related to the independent variable. This measures the proportion of variance in the dependent variable attributed to by the independent variables and tells us the proportion of the variance that no longer existed when we use the best fitting straight line. Standard error of estimate indicates the closeness with which the new estimated values approximate to the true, but unknown, values. Further information may be obtained from the excellent book by Ezekiel and Fox (26).

Resting Subjects

Examination of the results of multiple correlation and regression in resting subjects shows that though ROA significantly influences the other independent variables such as altitude and denitrogenation, it is not a significant predictor of the outcome of DCS (tables 4,6).

Examination of ascent rates with respect to TR in resting subjects is given in figures 14 and 15. The incidence of symptoms of DCS shows a good correlation with the linear fit of data with respect to TR in the case of ROA of 3000 ft/min and is limited by the small number of experiments at 5000 ft/min.

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The frequency distribution of ROA in these subjects is given in figure 16 and, in combination with table 9, offers useful information.

Thus, in general ROA appears to be of no major concern in resting subjects (up to 5000 ft/min). However, the effects of rates below and above 2500 ft/min are different on the incidence of symptoms (table 9) in the cases examined.

Exercising Subjects

The picture is much different with exercise at altitude. ROA has a significant correlation with the other independent variables like altitude, denitrogenation, duration of stay, and exercise frequency. This relationship is significantly evident in all exercise cases put together, as well as in cases with no denitrogenation. The combination of all these factors also significantly influence the incidence of symptoms and forced descent in these instances (table 5). However, under denitrogenation, ROA shows no significant influence with these independent factors and in combination significantly influences only forced descent and not symptoms (table 5).

The results of the multiple regression analysis show that ROA is a significant predictor of the incidence of forced descent in denitrogenated subjects exercising at altitude (table 7) while not a predictor in the other cases. This finding is interesting and warrants a look at the distribution of experiments in the conditions involving denitrogenation and exercise. Out of 52 experiments falling under exercise with prior denitrogenation, approximately 3/5 employed rates greater than 5500 ft/min (mean=9400; S.E. = 1552), while out of 69 experiments without denitrogenation and exercise, approximately 2/12 employed rates above 5500 ft/min (mean=4257; S.E. = 345). Further, the former category of experiments employed exercise frequencies equally above and below 12 cycles/per hour while the latter employed frequencies above 12 cycles/hour in 65 percent of the experiments. The effect of high exercise frequency on DCS in the nondenitrogenated experiments seems to have been offset by the low rates of ascent employed under these conditions and do not allow us to draw specific conclusions.

Tests of independence on the exercise data show that the incidence of DCS among ROA groups are heterogeneous in all these studies and in nondenitrogenated and denitrogenated cases taken separately (tables 10,11,12). However, the data are homogenous at ROA groups above and below 2500 ft/min only in denitrogenated subjects (table 12) and not in the rest (tables 10,11).

Tests of independence further show that the effects of ascent rates above 2500 ft/min are homogenous in all the cases except where exercise and denitrogenation occur in combination. These findings would indicate that under denitrogenation and exercise, the effects of ascent rates are crucial in determining the outcome, whatever the rates may be. But these observations are not conclusive since the combined effects of altitude attained, denitrogenation, and exercise on DCS are variable and are further limited by the distribution of data and statistical methods employed in this study. This adds further dimension to the problem of the combined effects of denitrogenation, exercise, and ascent rates on DCS.

Tissue ratio is the only alternative concept available to combine the effects of altitude and denitrogenation and its advantages were discussed in the section entitled "Tissue Ratio Concept." But it does not include the effects of exercise. The incidence of symptoms of DCS under different rates of ascent with respect to TR in exercising subjects is illustrated in figures 17 through 21 along with their frequency distribution in figure 22. Symptoms of DCS at different ROA show good correlation with the linear fit of data with respect to TR. As the TR increases, the incidence of symptoms of DCS increases under the same rates of ascent. Examination of table 10 along with these figures provide useful information on the effect of ascent rates in the population examined.

All Cases

It was observed earlier that ROA was not a significant predictor of symptoms in all the cases pooled together, though it showed significant correlation with the other independent variables (table 3). Tests of independence further show that though the data are heterogeneous with respect to the various ROA groups, there is homogeneity at rates above 2500 ft/min (table 8). The incidence of symptoms and forced descent are significantly different between the groups with ascent rates below and above 2500 ft/min (table 8). This would support some of the earlier observations that the effects of slow ascent rates are different from those of the commonly used rates in decompression (6).

IMPLICATIONS OF THE FINDINGS

Examination of the findings in this study show close interaction of altitude, denitrogenation, and exercise with the effects of ROA. Rate of ascent is not a significant predictor of the incidence of DCS in the population examined. However, it has a significant correlation with the other independent factors and in combination with these factors significantly influences the onset of DCS.

It has been seen in the section entitled "Influence of ROA and Denitrogenation at 38,000 Ft," that at any particular altitude the effects of ROA are not significantly different under varying periods of denitrogenation. The shape of Behnke's nitrogen elimination curve and the experiments by Gray on resting and Clarke et.al., on exercising subjects show that denitrogenation for short periods of time could positively influence the outcome of DCS (15,36). As the elimination of nitrogen is maximum during the first 20 to 30 minutes (7,33,54), it appears that even short preoxygenation periods along with slow rates of ascent (below 2500 ft/min) to altitudes up to 38,000 ft would offer effective protection. At the same time Behnke's observation that the nitrogen eliminated during the first 1 hour of denitrogenation was not crucial to the onset of DCS is contrary to the protection obtained by Gray with short denitrogenation periods. It has also been observed by various workers that denitrogenation for periods greater than 1 hour does not add much to the protection against DCS (38,44,47) unless it is carried out for extended periods (20,21,67).

The protection offered by preoxygenation is limited whenever exercise is carried out at altitude (38,47). The data are significantly different at the various ROA examined in this study between resting and exercising

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subjects. (See section entitled "Influence of Exercise.") Further, ROA is a significant predictor of the incidence of DCS only in subjects exercising at altitude with prior denitrogenation. (See section entitled "Exercising Subjects.") Segregation of the effects of altitude, denitrogenation, exercise, and ascent rates on DCS is difficult, and TR is a useful reference for such purposes. However, it does not include the effects of exercise. Hence, the examination of the effects of different ascent rates on DCS with respect to TR separately in resting and exercising subjects in this study seems justified.

The picture is further clouded by the observations of Armstrong that low rates of ascent decrease altitude tolerance by increasing the period of exposure (6). Ascent rates below 2500 ft/min show a higher incidence of DCS in our analysis (figs. 16 and 22). However, this may be due to the higher altitudes and tissue ratios employed under these rates (appendix B) and therefore not clear from the existing evidence.

SUMMARY

The results of our analysis may be summarized as follows:

1. Tissue ratio is a useful concept for including the effects of altitude, denitrogenation, and time taken for ascent and denitrogenation during this period, if any.

2. Denitrogenation during ascent appears to be possible, but the effectiveness of such a period of denitrogenation is likely to be less with increasing altitudes.

3. The effects of rate of ascent, altitude, denitrogenation, and exercise are closely interrelated.

4. The effects of denitrogenation are different with various ascent rates in resting and exercising subjects. However, at any particular altitude examined, the effects of specific ascent rates are not significantly different with various periods of denitrogenation.

5. At different ascent rates, exercise at altitude appears to be a more important variable than prior ground level denitrogenation in influencing the incidence of DCS.

6. Though the effects of ascent rates are not essentially different above 2500 ft/min, individual group differences may exist.

7. Higher rates of ascent (above 10,000 ft/min) do not influence the outcome of DCS differently, though at intermediary ascent rates (between 2500 ft/min to 10,000 ft/min) the effects are varying. This may be due to the different types of exercise and various periods of denitrogenation examined in this study.

8. The effects of ascent rates below 2500 ft/min are significantly different from the rates above 2500 ft/min. This trend is evident in all studies

taken together and studies involving rest or exercise at altitude taken separately.

9. In general, rate of ascent is not a significant predictor of the incidence of DCS in the population examined.

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TABLE 1.- NUMBER OF MAN-FLIGHTS EXAMINED IN THE PRESENT ANALYSIS

	No denitrogenation	With denitrogenation	Total
Rest at altitude	5897	692	6589
Exercise at altitude	5885	1649	7534
Total	11782	2341	14123

TABLE 2.- NUMBER OF MAN-FLIGHTS EXAMINED WITH RESPECT TO VARIOUS ASCENT RATES

Rates of ascent (ft/min)	Rest at altitude		Exercise at altitude	
	No denitro	Denitro	No denitro	Denitro
< 2500	4342	-	250	122
2501 - 3500	1156	33	2876	195
3501 - 5500	399	659	802	752
5501 - 10500	-	-	1848	449
10501 - 20500	-	-	109	65
> 20501	-	-	-	66

TABLE 3.- MULTIPLE CORRELATION AND REGRESSION ANALYSIS ON ALL THE EXPERIMENTS

a. Multiple correlation of ascent rates on all the other independent variables (altitude, denitrogenation, duration of stay, and exercise frequency) and tests of significance of multiple regression of ascent rates on the above parameters

	Multiple correlation R	Squared R	Significance of multiple regression
n=150	0.32	0.10	* P=0.004

b. Multiple correlation of all the independent variables (ascent rates, altitude, denitrogenation, duration of stay, and exercise frequency) on the symptoms and forced descent separately and tests of significance of their multiple regression

Symptoms (n=147)	0.87	0.76	* P=0.001
Forced descent (n=147)	0.73	0.54	* P=0.001

c. Regression coefficients for predicting symptoms and forced descent separately from rate of ascent and tests of significance of the regression coefficient given the other independent variables

	Regression coefficient(b)	Standard error	Significance
On symptoms	0.0002	0.0	P=0.26 n.s.
On forced descent	0.0002	0.0	P=0.40 n.s.

* P<0.05

TABLE 4.-MULTIPLE CORRELATION OF RATE OF ASCENT IN STUDIES WITH REST AT ALTITUDE

a. Multiple correlation of rate of ascent with the other independent variables (altitude, denitrogenation) and tests of significance of multiple regression of independent variables using F-statistic

	Multiple correlation coefficient (R)	Squared multiple correlation (R^2)	Significance of multiple regression
1. All studies (n=26)	0.43	0.19	P=0.10 n.s.
2. Studies with no denitrogenation (n=20)	0.18	0.03	P=0.44 n.s.

b. Multiple correlation of incidence of symptoms and forced descent separately with all the independent variables (rate of ascent, altitude, denitrogenation) and tests of significance of multiple regression of each dependent variable with the independent variables using F-statistic

	Symptoms			Forced descent		
	R	R^2	Significance	R	R^2	Significance
1. All studies (n=26)	0.70	0.50	* P=0.001	0.74	0.54	* P=0.006
2. Studies with no denitro (n=20)	0.91	0.83	* P=0.001	0.85	0.73	* P=0.001

* $P<0.05$

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TABLE 5.- MULTIPLE CORRELATION OF RATE OF ASCENT IN STUDIES WITH EXERCISE AT ALTITUDE

a. Multiple correlation of rate of ascent with other independent variables (altitude, denitrogenation, duration of stay at altitude, and exercise frequency) and tests of significance of multiple regression of the independent variables using F-statistic

	Multiple correlation coefficient (R)	Squared multiple correlation (R^2)	Significance of multiple regression
1. All studies (n=119)	0.30	0.09	P=0.02 *
2. Studies with no denitrogenation (n=69)	0.72	0.51	P=0.001 *
3. Studies with denitrogenation (n=41)	0.51	0.26	P=0.028 *

b. Multiple correlation of incidence of symptoms and forced descent separately with all the independent variables (altitude, rate of ascent, denitrogenation, exercise frequency, duration of stay at altitude) and tests of significance of multiple regression of each dependent variable with all the independent variables using F-statistic

	Symptoms			Forced descent		
	R	R^2	Significance	R	R^2	Significance
1. All studies (n=119)	0.88	0.76	* P=0.001	0.80	0.64	* P=0.001
2. Studies with no denitro (n=69)	0.93	0.86	* P=0.001	0.81	0.66	* P=0.001
3. Studies with denitrogenation (n=41)	0.15	0.21	n.s. P=0.98	0.82	0.67	* P=0.001

* P<0.05

TABLE 6.- MULTIPLE REGRESSION OF RATE OF ASCENT IN RESTING SUBJECTS

Regression coefficient for predicting the incidence of symptoms and forced descent (dependent variables) separately from rate of ascent in the presence of other independent variables (altitude, denitrogenation) is given. Tests of significance of the regression coefficient of rate of ascent in predicting the outcome (incidence of symptoms, forced descent) separately in the presence of the other independent variables is also given.

		Symptoms			Forced descent		
		b	S.E.	Significance	b	S.E.	Significance
1.	All studies (n=28)	0.0015	0.004	n.s. P=0.70	0.0006	0.002	n.s. P=0.71
2.	Studies with no denitro (n=20)	0.001	0.002	n.s. P=0.71	0.001	0.001	n.s. P=0.50

b = regression coefficient; S.E. = standard error of regression coefficient

TABLE 7.- MULTIPLE REGRESSION OF RATE OF ASCENT IN EXERCISING SUBJECTS

Regression coefficients for predicting the incidence of symptoms and forced descent (dependent variables) separately from rate of ascent in the presence of other independent variables (altitude, denitrogenation, duration of stay, frequency of exercise) is given. Tests of significance of the regression coefficient of rate of ascent for predicting the outcome separately in the presence of other independent variables is also given.

		Symptoms			Forced descent		
		b	S.E.	Significance	b	S.E.	Significance
1.	All studies (n=119)	0.0001	0	n.s. P=0.62	0.0001	0	n.s. P=0.96
2.	Studies with no denitro (n=69)	0.0005	0.001	n.s. P=0.55	-0.0012	0.001	n.s. P=0.38
3.	Studies with denitro (n=41)	-54.12	82.96	n.s. P=0.52	-0.386	0.131	* P=0.006

b = regression coefficient; S.E. = standard error of regression coefficient

* P<0.05

TABLE 8.- TESTS OF INDEPENDENCE OF ASCENT RATES IN ALL THE EXPERIMENTS ON DCS

Group	Ascent rates (ft/min)	Symptoms	Forced descent
I	< 2500 2501 - 3500	P=0.03 *	P=0.02 *
II	2501 - 3500 3501 - 5500	P=0.93 n.s.	P=0.67 n.s.
III	3501 - 5500 5501 - 10500	P=0.09 n.s.	P=0.02 *
IV	5501 - 10500 10501 - 20500	P=0.03 *	P=0.04 *
V	10501 - 20500 > 20501	P=0.83 n.s.	P=0.29 n.s.
VI	All rates	P=0.08 n.s.	P=0.03 *
VII	2501 - 3500 3501 - 5500 5501 - 10500 10501 - 20500 > 20501	P=0.27 n.s.	P=0.13 n.s.
VIII	< 2500 > 2501	P=0.03 *	P=0.01 *

Tests of independence using Mann-Whitney's U-Test or Kruskal-Wallis one-way analysis of variance, as applicable

* P<0.05

TABLE 9.- SIGNIFICANCE OF THE TESTS OF INDEPENDENCE FOR DIFFERENT ASCENT RATES IN RESTING SUBJECTS

Group	Ascent rates (ft/min)	Symptoms	Forced descent
I	< 2500 2501 - 3500	P=0.01 *	P=0.008 *
II	2501 - 3500 3501 - 5500	P=0.44 n.s.	P=0.11 n.s.
III	< 2500 2501 - 3500 3501 - 5500	P=0.04 *	P=0.06 n.s.
IV	< 2500 > 2501	P=0.02 *	P=0.15 n.s.

Tests of independence using Mann-Whitney's U-Test or Kruskal-Wallis one-way analysis of variance, where appropriate

* P <0.05

TABLE 10.- SIGNIFICANCE OF THE TESTS OF INDEPENDENCE FOR DIFFERENT ASCENT
RATES IN EXERCISING SUBJECTS

Group	Ascent rates (ft/min)	Symptoms	Forced descent
I	< 2500 2501 - 3500	P=0.04 *	P=0.01 *
II	2501 - 3500 3501 - 5500	P=0.95 n.s.	P=0.89 n.s.
III	3501 - 5500 5501 - 10500	P=0.06 n.s.	P=0.02 *
IV	5501 - 10500 10501 - 20500	P=0.03 *	P=0.04 *
V	10501 - 20500 > 20501	P=0.83 n.s.	P=0.29 n.s.
VI	All groups	P=0.07 n.s.	P=0.01 *
VII	2501 - 3500 3501 - 5500 5501 - 10500 10501 - 20500 > 20501	P=0.21 n.s.	P=0.11 n.s.
VIII	< 2500 > 2501	P=0.04 *	P=0.006 *

Tests of independence using Mann-Whitney's U-Test or Kruskal-Wallis one-way
analysis of variance, where appropriate

* $P<0.05$

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TABLE 11.- TESTS OF INDEPENDENCE OF ASCENT RATES ON SUBJECTS WITH NO
PRIOR DENITROGENATION AND RESTING OR EXERCISING AT ALTITUDE

Group	Ascent rates (ft/min)	Symptoms	Forced descent
a. Resting subjects:			
I	< 2500		
	2501 - 3500	P=0.01 *	P=0.008 *
II	2501 - 3500		
	3501 - 5500	P=0.01 *	P=0.008 *
III	All rates	P=0.007*	P=0.004 *
IV	< 2500		
	> 2501	P=0.04 *	P=0.47 n.s.
b. Exercising subjects:			
I	< 2500		
	2501 - 3500	P=0.01 *	P=0.02 *
II	2501 - 3500		
	3501 - 5500	P=0.61 n.s.	P=0.68 n.s.
III	All rates	P=0.09 n.s.	P=0.07 n.s.
IV	< 2500		
	> 2501	P=0.04 *	P=0.02 *

Tests of independence using Mann-Whitney's U-Test or Kruskal-Wallis one-way
analysis of variance, as applicable

* P<0.05

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TABLE 12.- TESTS OF INDEPENDENCE ON SUBJECTS WITH PRIOR DENITROGENATION AND EXERCISING AT ALTITUDE

Group	Ascent rates (ft/min)	Symptoms	Forced descent
I	< 2500 2501 - 3500	P=0.08 n.s.	P=0.03 *
II	2501 - 3500 3501 - 5500	P=0.04 *	P=0.03 *
III	3501 - 5500 5501 - 10500	P=0.01 *	P=0.01 *
	5501 - 10500 10501 - 20500	P=0.04 *	P=0.05 *
V	10501 - 20500 > 20501	P=0.76 n.s.	P=0.65 n.s.
VI	All rates	P=0.03 *	P=0.02 *
VII	2501 - 3500 3501 - 5500 5501 - 10500 10501 - 20500 > 20501	P=0.02 •	P=0.03 *
VIII	< 2500 > 2501	P=0.41 n.s.	P=0.08 n.s.

Tests of independence using Mann-Whitney's U-Test or Kruskal-Wallis one-way analysis of variance, where applicable

* P<0.05

TABLE 13.- OTHER TESTS OF INDEPENDENCE

Parameter		Ascent rates (ft/min)	Symptoms	Forced descent
1.	Denitro + exercise:			
	a. At 35,000 ft altitude	2501 - 3500		
		3501 - 5500	P=0.22 n.s.	P=0.39 n.s.
	b. At 38,000 ft altitude	< 2500		
		3501 - 5500	P=0.54 n.s.	P=0.37 n.s.
2.	All studies:			
	c. Rest vs exercise	All rates	P=0.01 *	P=0.007 *
	c. Rest vs exercise	2501 - 3500	P=0.006 *	P=0.004 *
	d. Rest vs exercise	3501 - 5500	P=0.05 *	P=0.12 n.s.

Tests of independence using Mann-Whitney's U-Test or Kruskal-Wallis one-way analysis of variance, where applicable

* $P < 0.05$

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SYMPTOMS □

FORCED DESCENT ◆

$y = -172.01 + 6.2460e-3x \quad R^2 = 0.793$

$y = -87.219 + 3.0986e-3x \quad R^2 = 0.736$

PERCENT INCIDENCE

ALTITUDE - FT

Figure 1. - Incidence of DCS in resting subjects at various altitudes without prior denitrogenation.
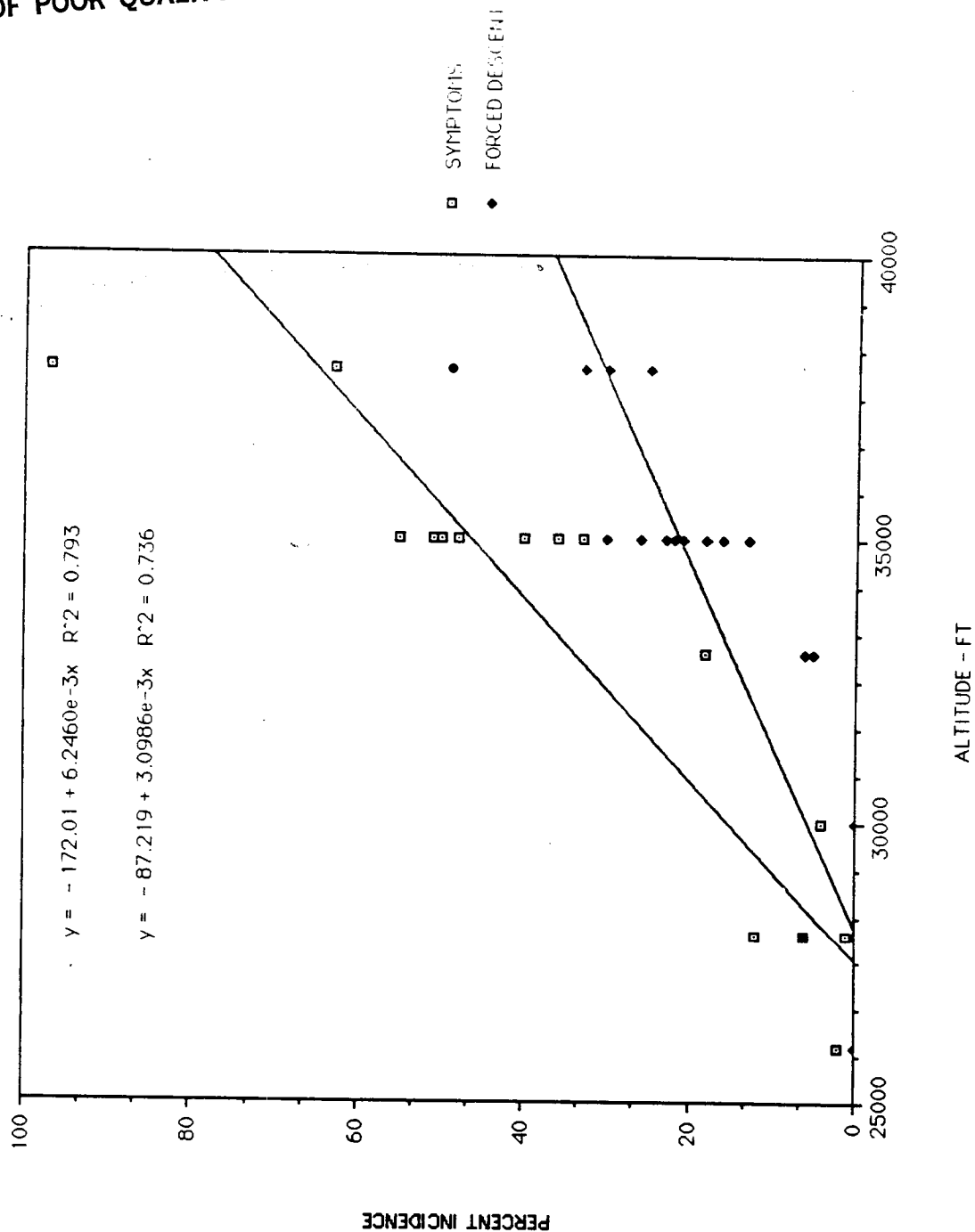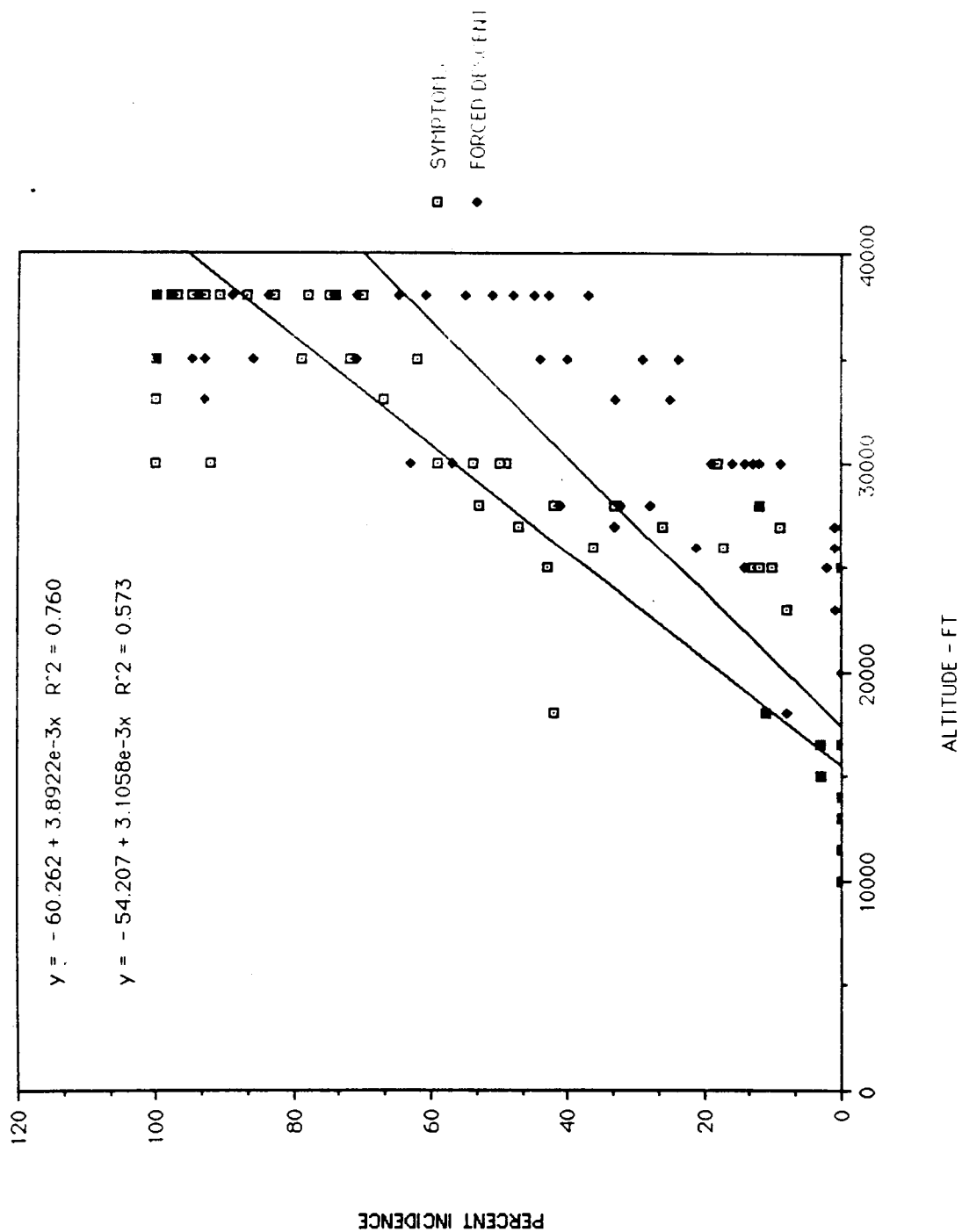
Figure 2. - Incidence of DCS in exercising subjects at various altitudes without prior denitrogenation.

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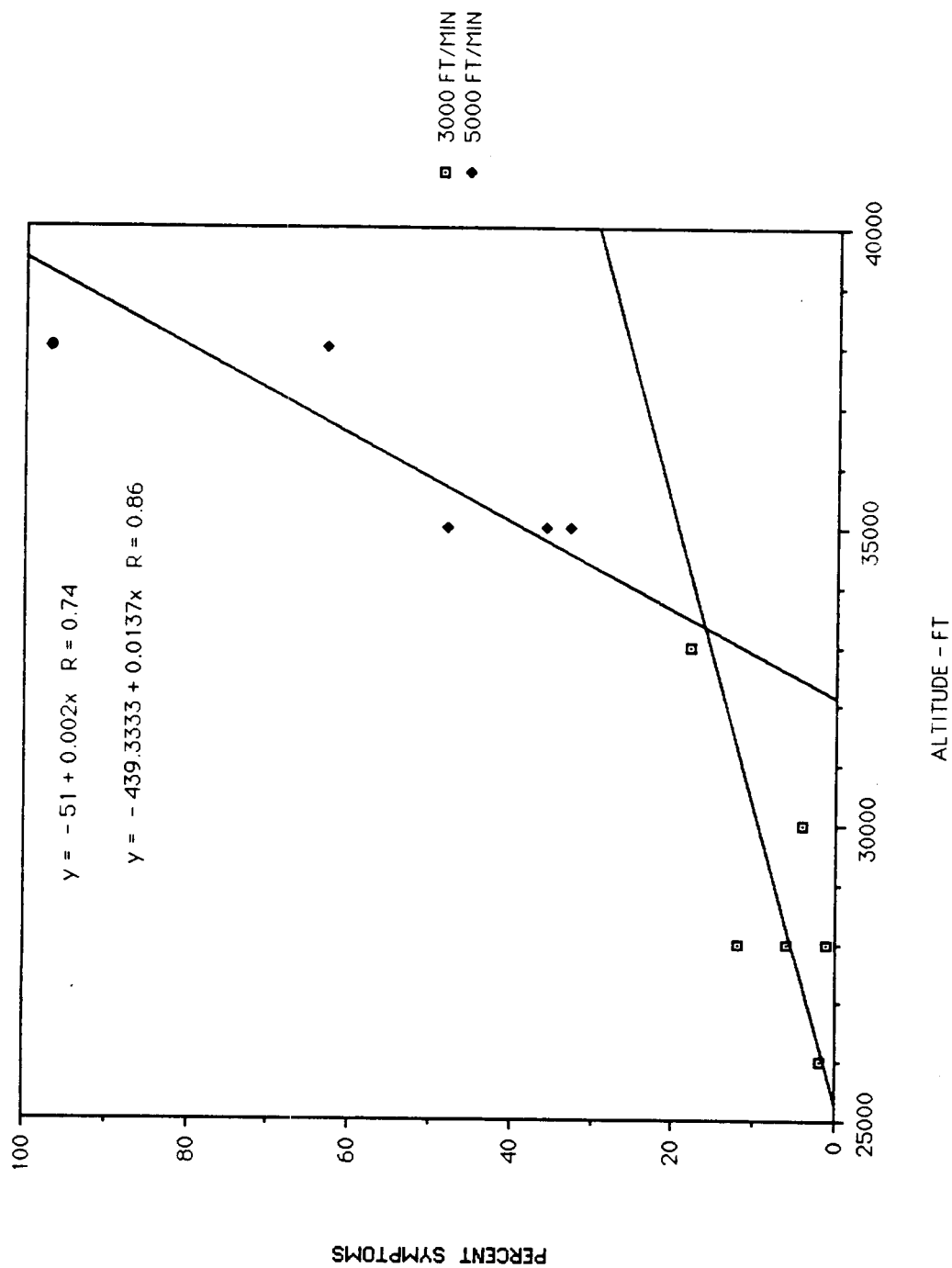
Figure 3. — Incidence of symptoms at 3000 ft/min and 5000 ft/min ascent rates in resting subjects without prior denitrogenation.

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Figure 4. – Incidence of symptoms at 3000 ft/min and 5000 ft/min rates of ascent in exercising subjects without prior denitrogenation.

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DENITROGENATION - HRS
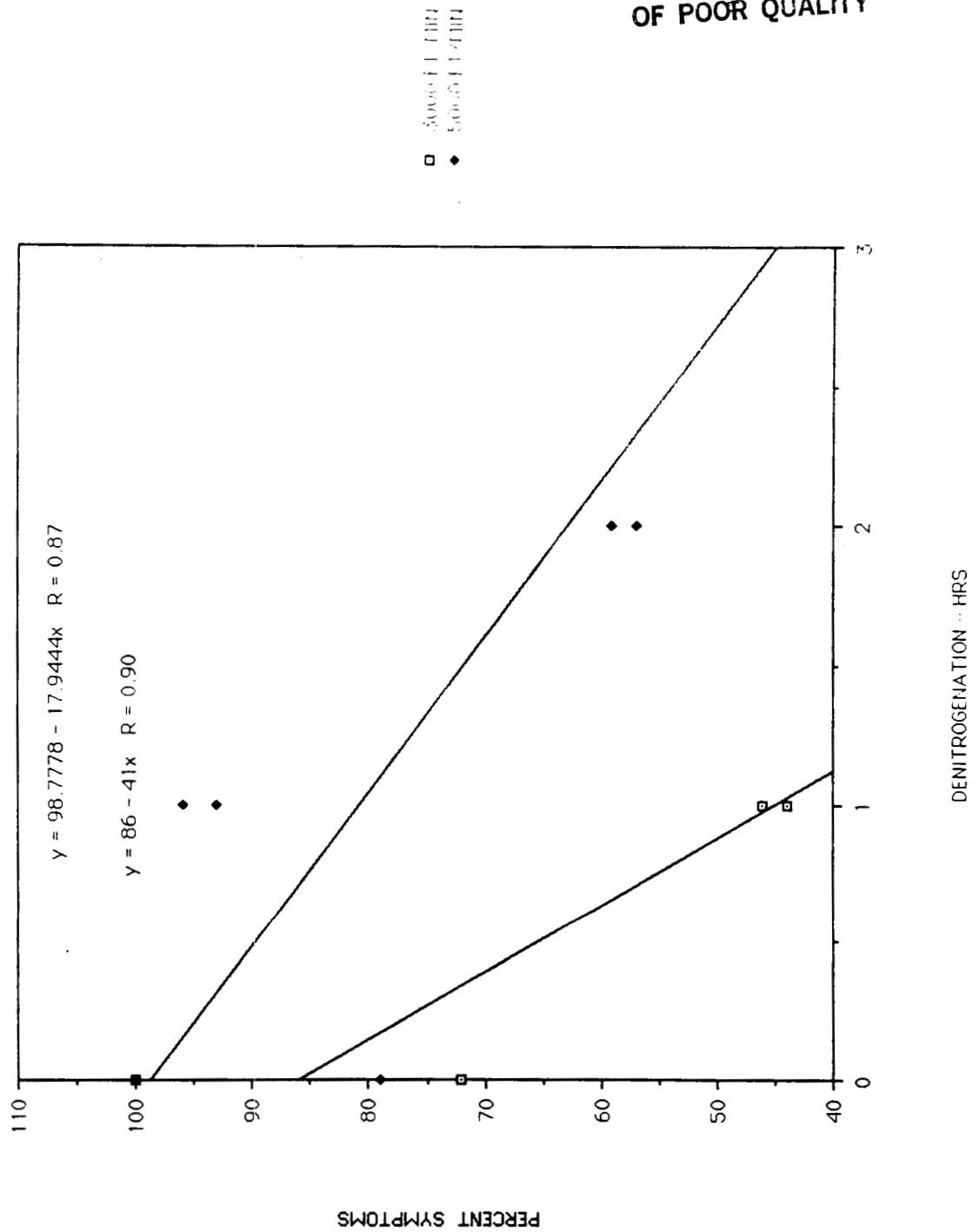
Figure 5. - Incidence of symptoms at 35,000 ft at two rates of ascent and with various periods of denitrogenation in subjects exercising at altitude.

PERCENT SYMPTOMS

$y = 98.7778 - 17.9444x$ $R = 0.87$

$y = 86 - 41x$ $R = 0.90$
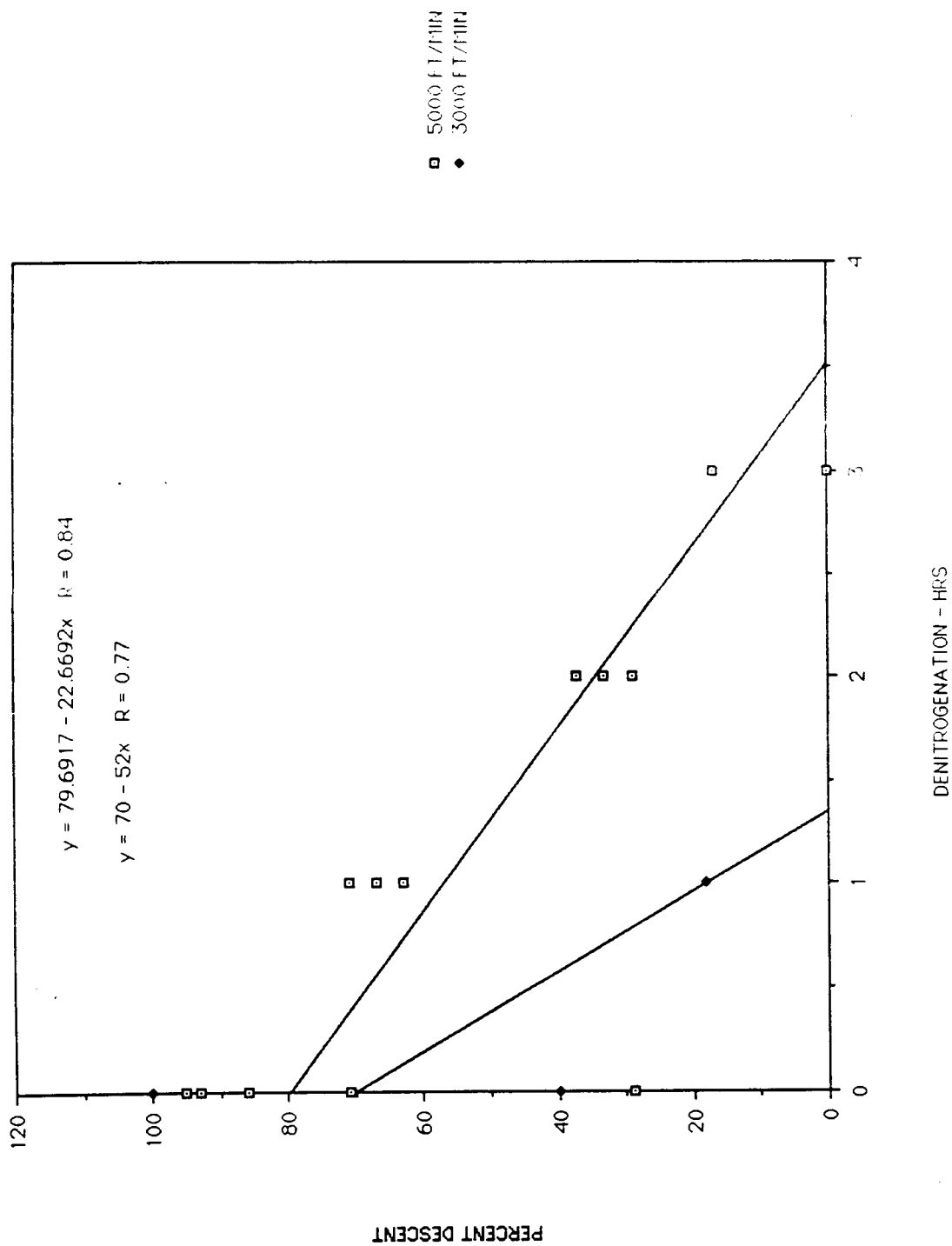
Figure 6. – Incidence of forced descent at 35,000 ft under varying periods of denitrogenation in the same studies as in figure 5.
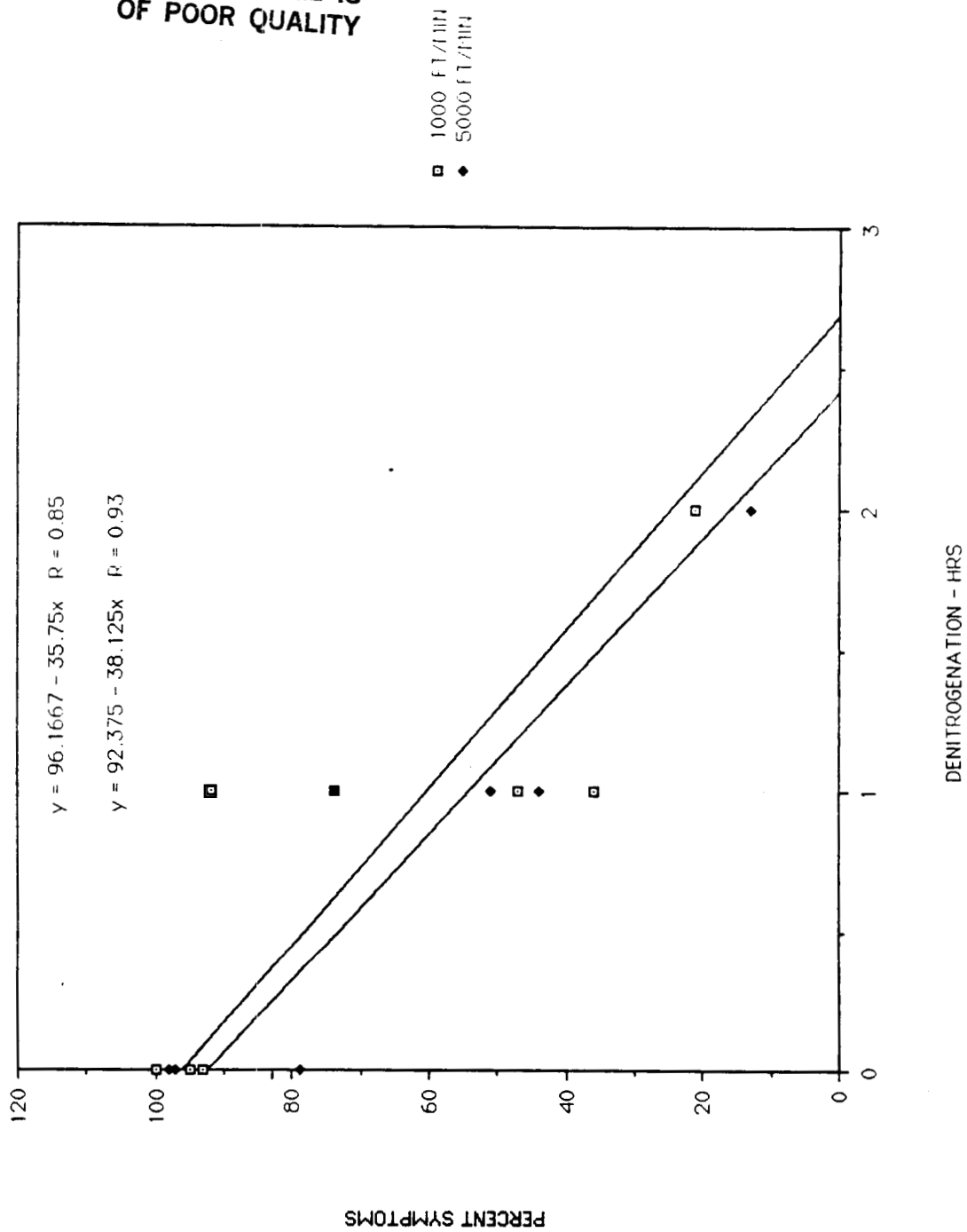
Figure 7. – Incidence of symptoms at 38,000 ft at two rates of ascent and with various periods of denitrogenation in subjects exercising at altitude.

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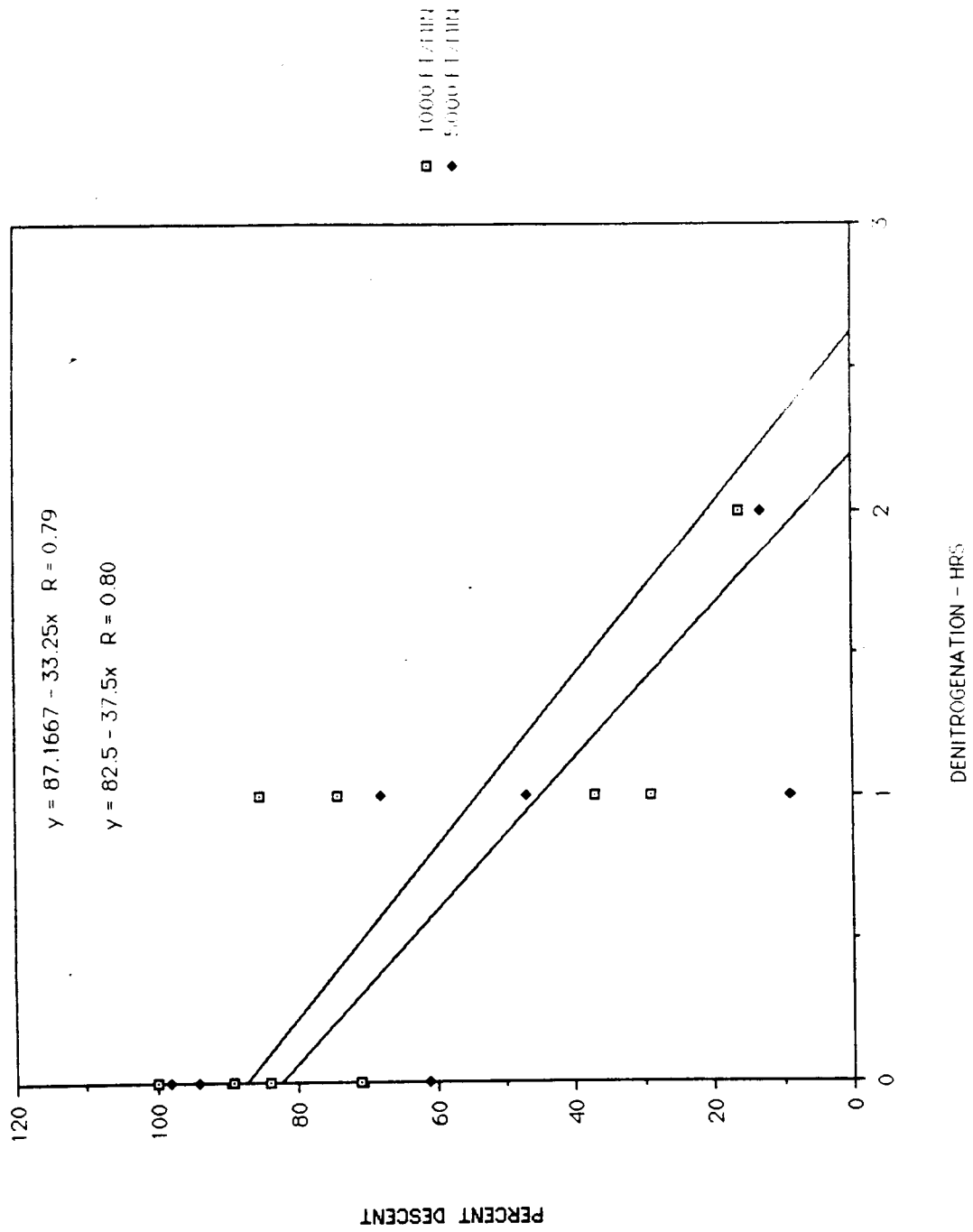
Figure 8. - Incidence of forced descent at 38,000 ft under varying periods of denitrogenation in the same studies as in figure 7.
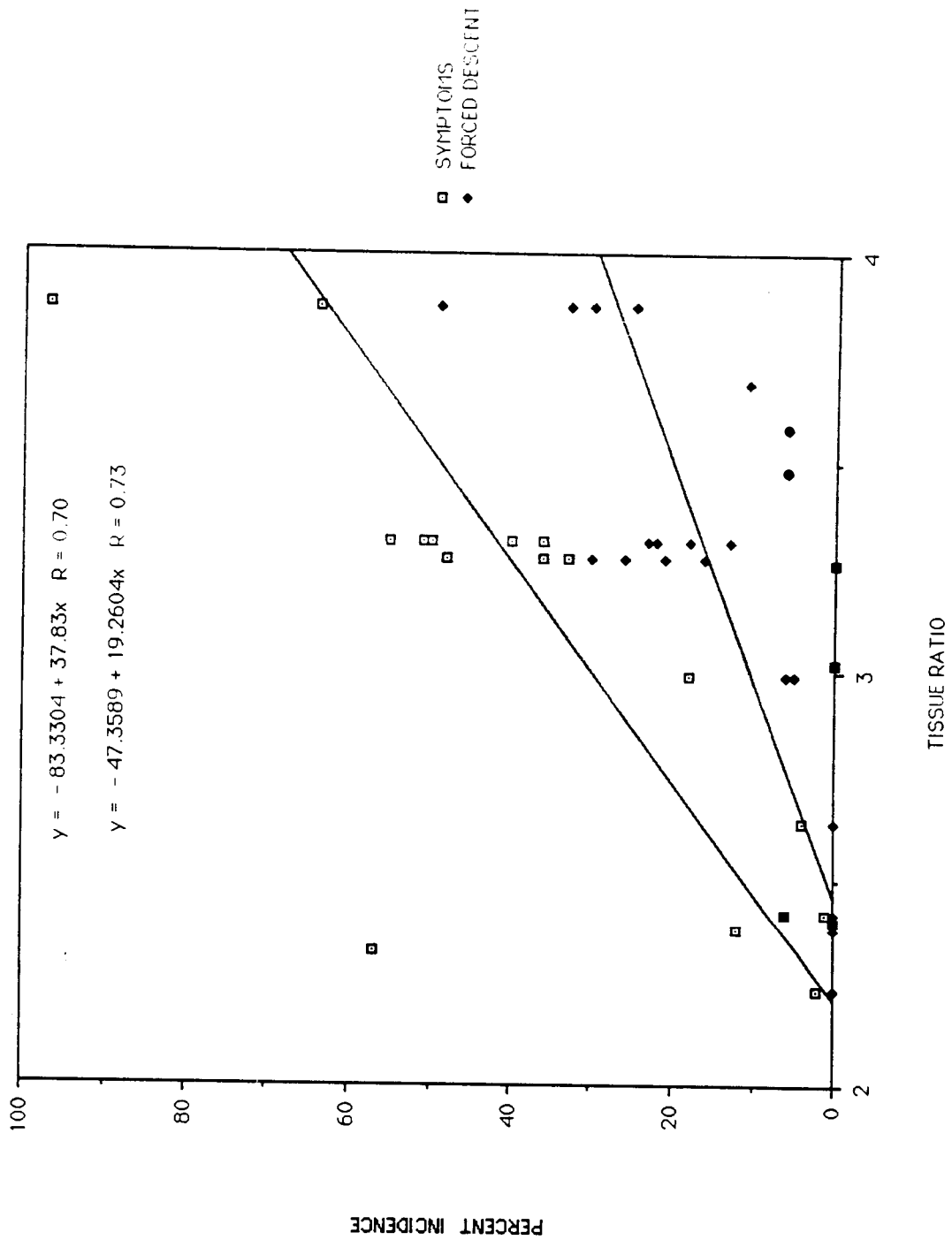
Figure 9. - Incidence of DCS in resting subjects at various tissue ratios.

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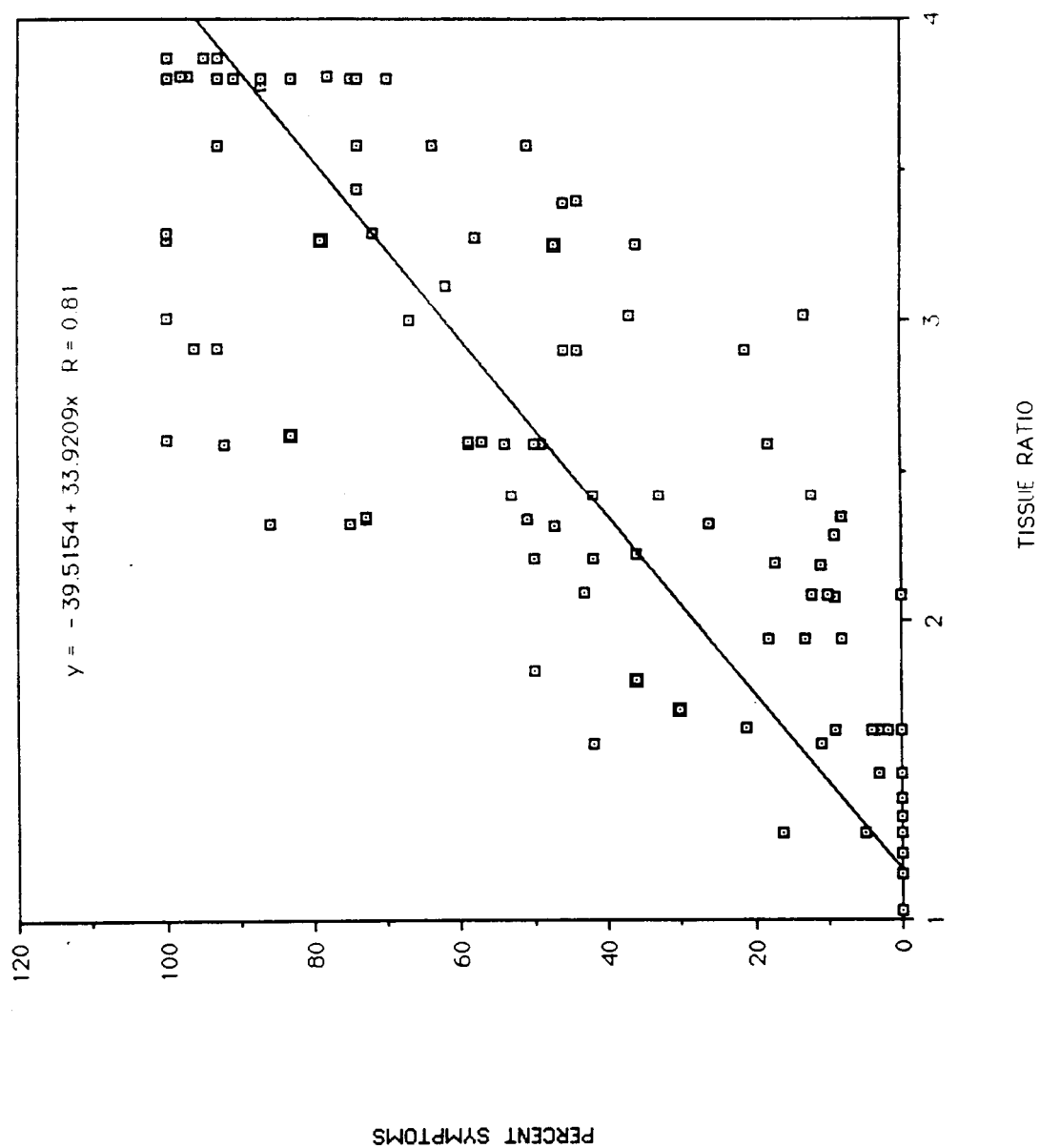
Figure 10. - Incidence of symptoms in exercising subjects at various tissue ratios.

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$$y = -42.3953 + 29.0493x \quad R = 0.78$$

TISSUE RATIO

PERCENT FORCED DESCENT

Figure 11. - Incidence of forced descent in exercising subjects at various tissue ratios.

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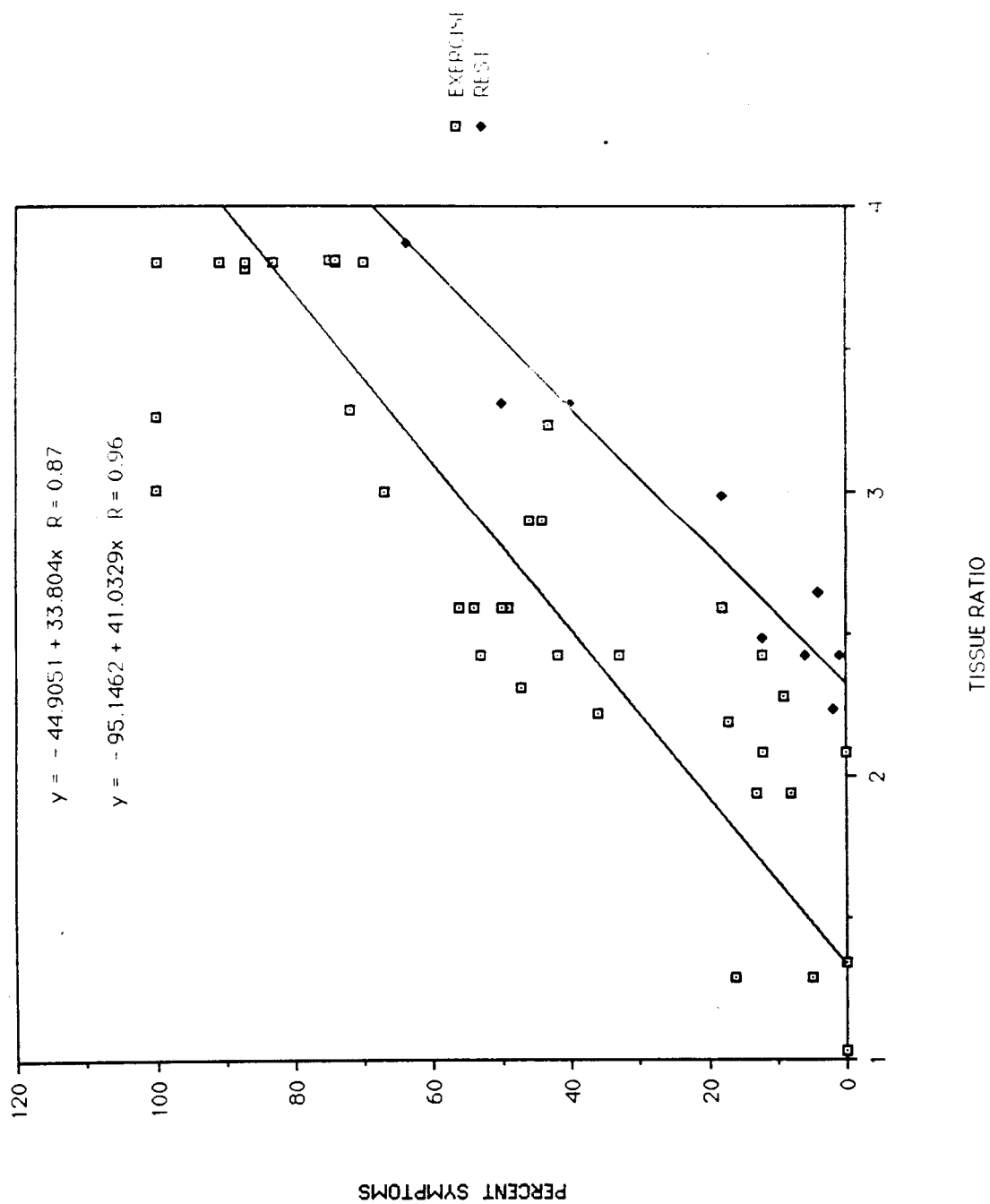
Figure 12. – Incidence of symptoms at 3000 ft/min rate of ascent in subjects resting or exercising at altitude.
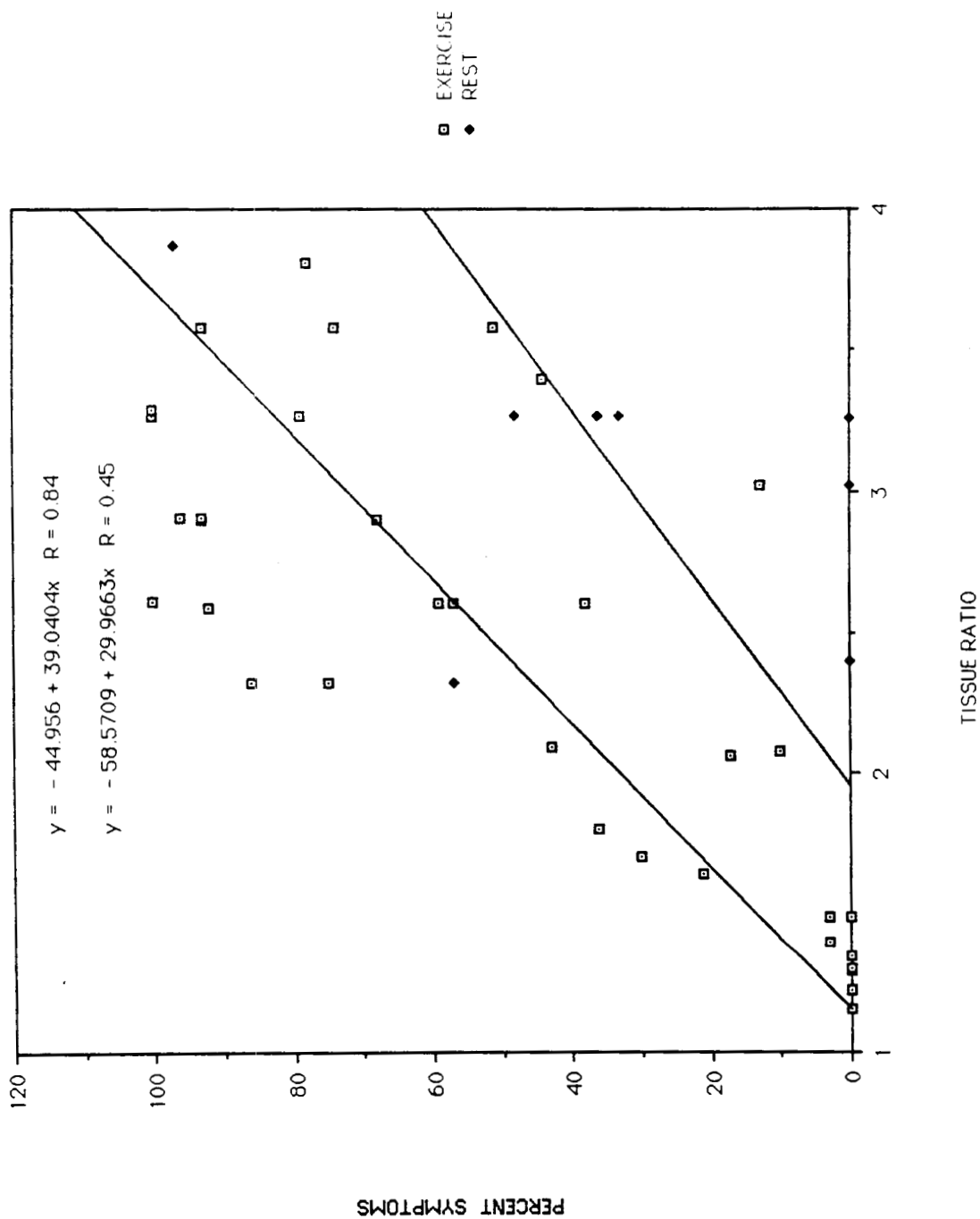
Figure 13. – Incidence of symptoms at 5000 ft/min ascent rate in subjects resting or exercising at altitude.

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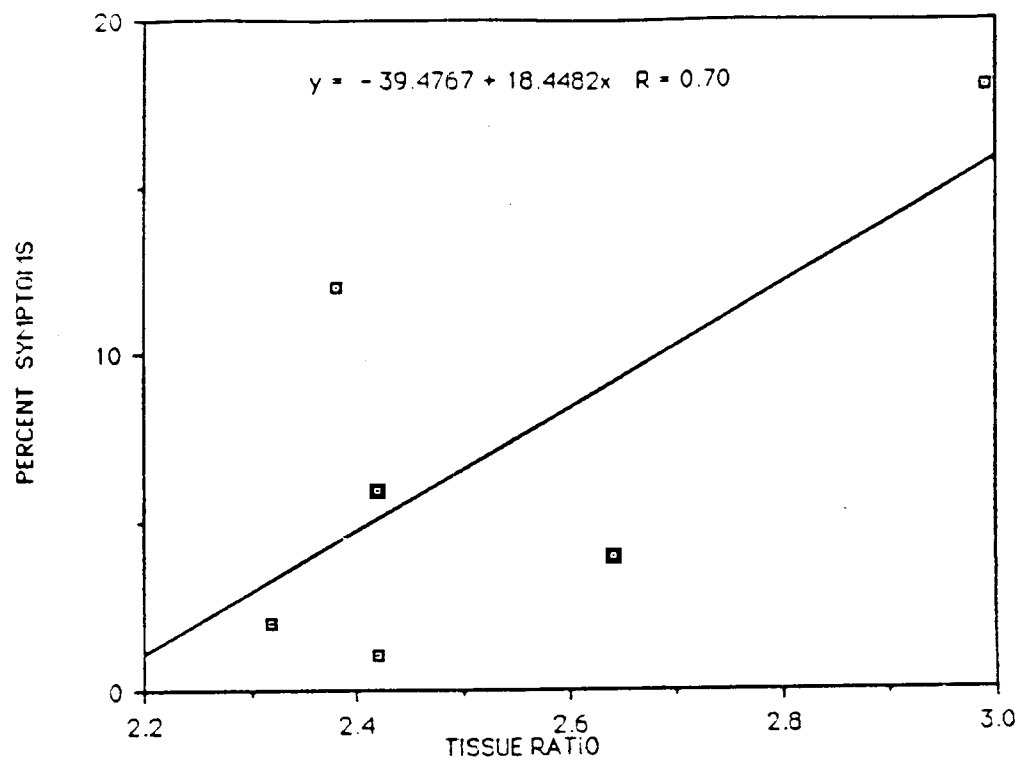
Figure 14. - Incidence of symptoms at ascent rate of 3000 ft/min in resting subjects.
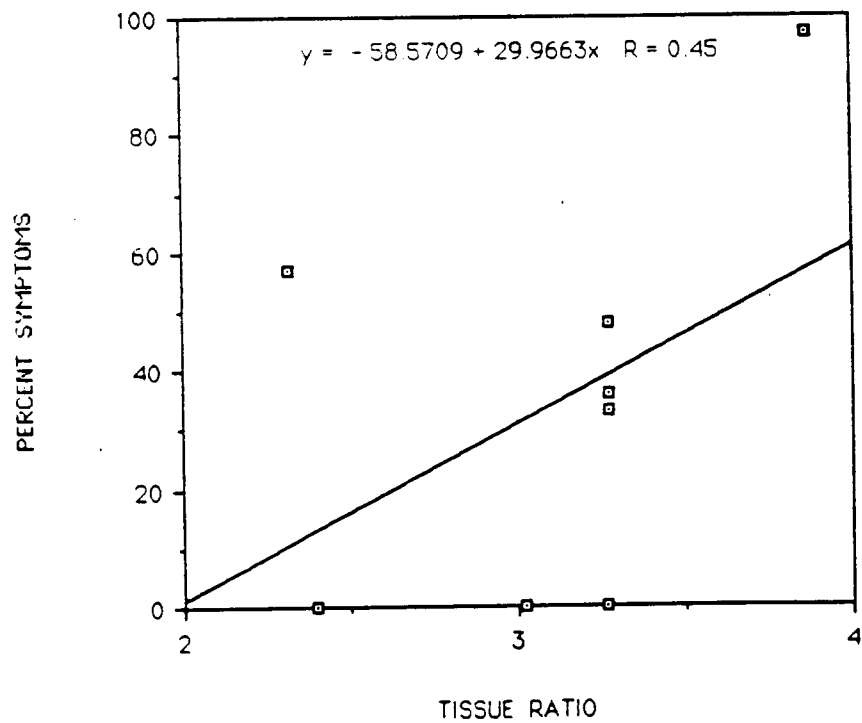
Figure 15. - Incidence of symptoms at ascent rate of 5000 ft/min in resting subjects.

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■ SYMPTOMS
▨ FORCED DESCENT
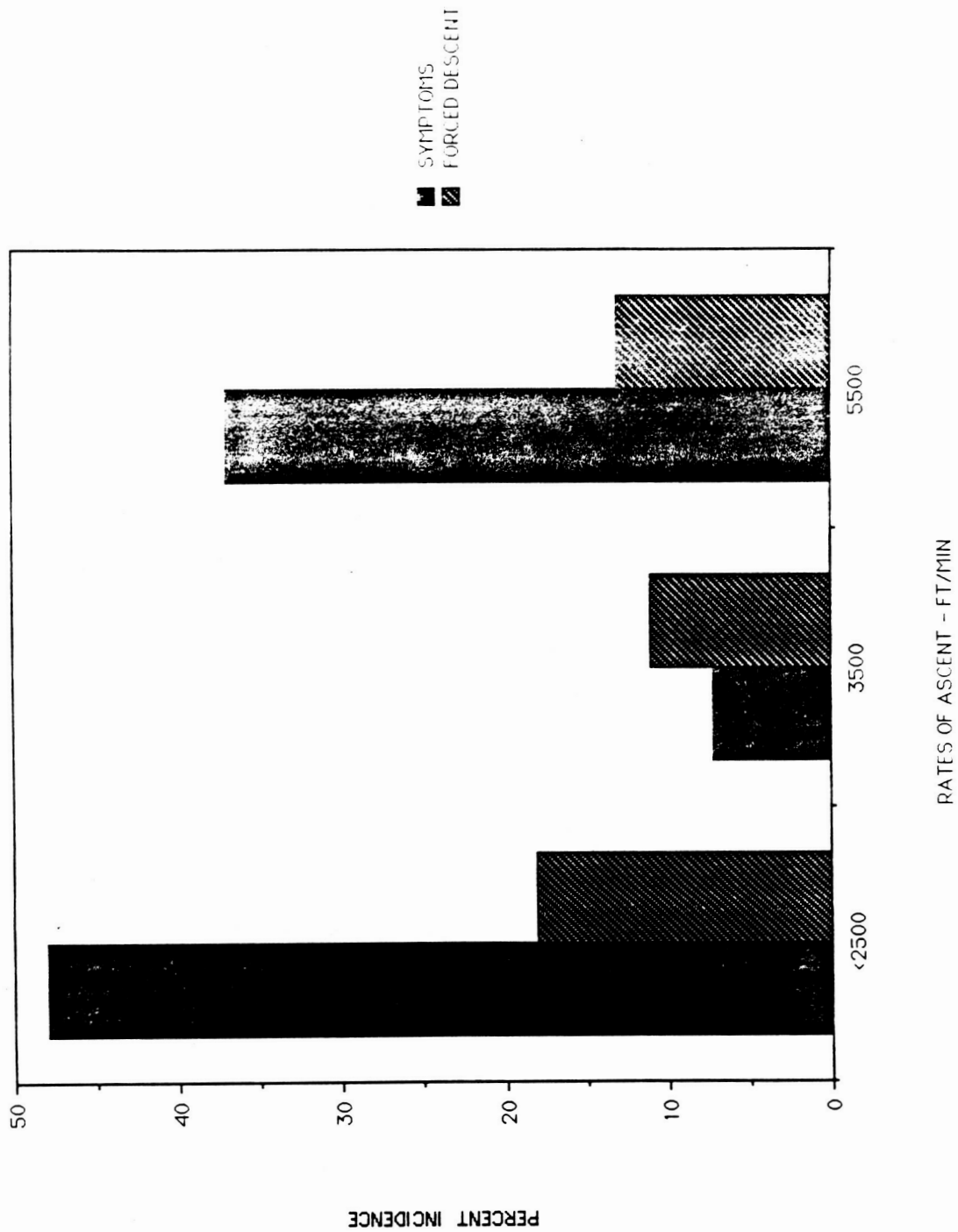
Figure 16. - Distribution of DCS under various rates of ascent
in subjects resting at altitude.
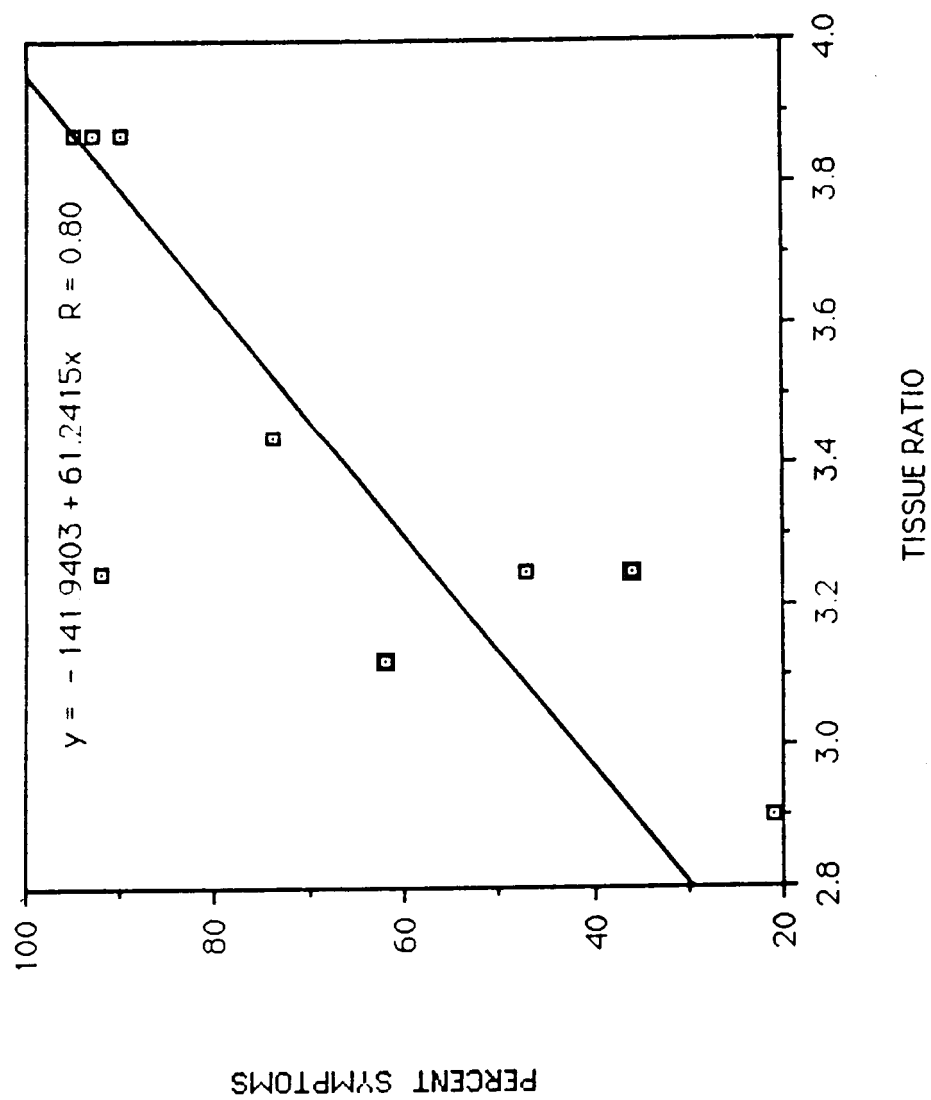
Figure 17. – Incidence of symptoms at ascent rate of 1000 ft/min in subjects exercising at altitude.

$$y = -141.9403 + 61.2415x \quad R = 0.80$$

PERCENT SYMPTOMS

TISSUE RATIO

$$y = -44.9051 + 33.804x \quad R = 0.87$$
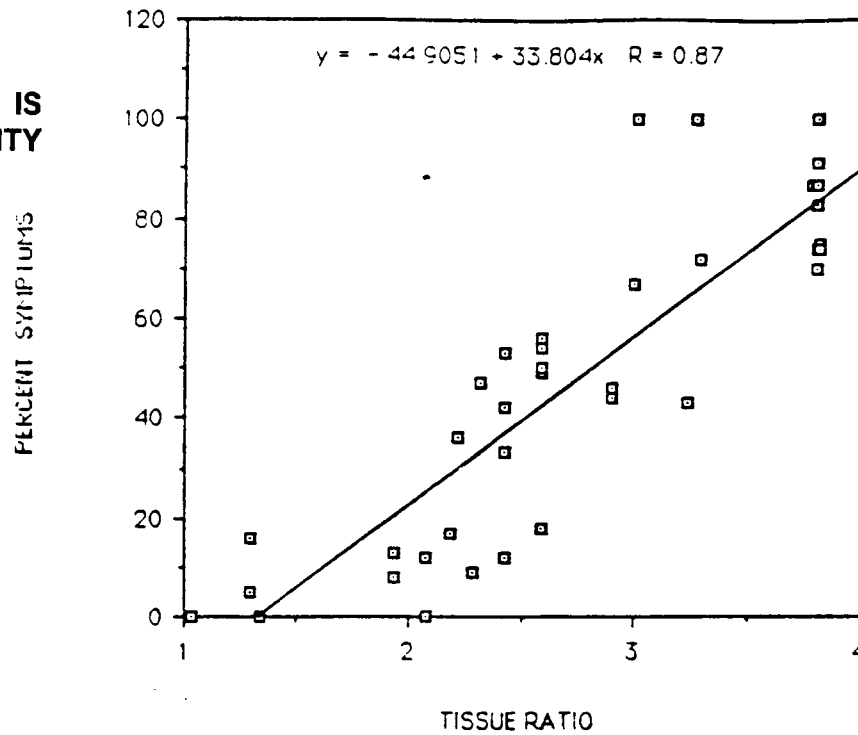
Figure 18. - Incidence of symptoms at ascent rate of 3000 ft/min
in subjects exercising at altitude.

$$y = -44.956 + 39.0404x \quad R = 0.84$$
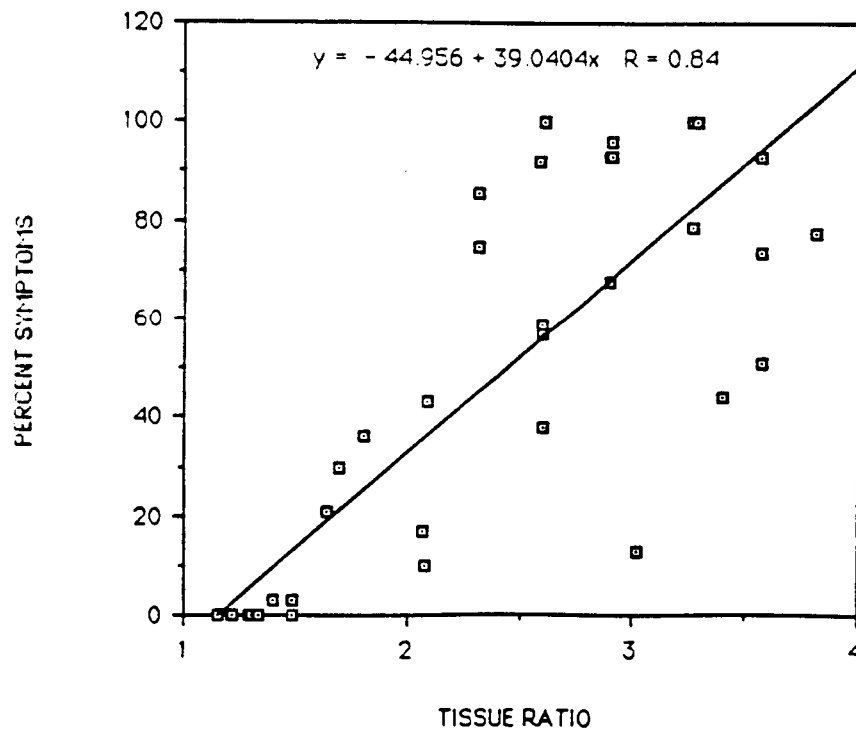
Figure 19. - Incidence of symptoms at ascent rate of 5000 ft/min
in subjects exercising at altitude.

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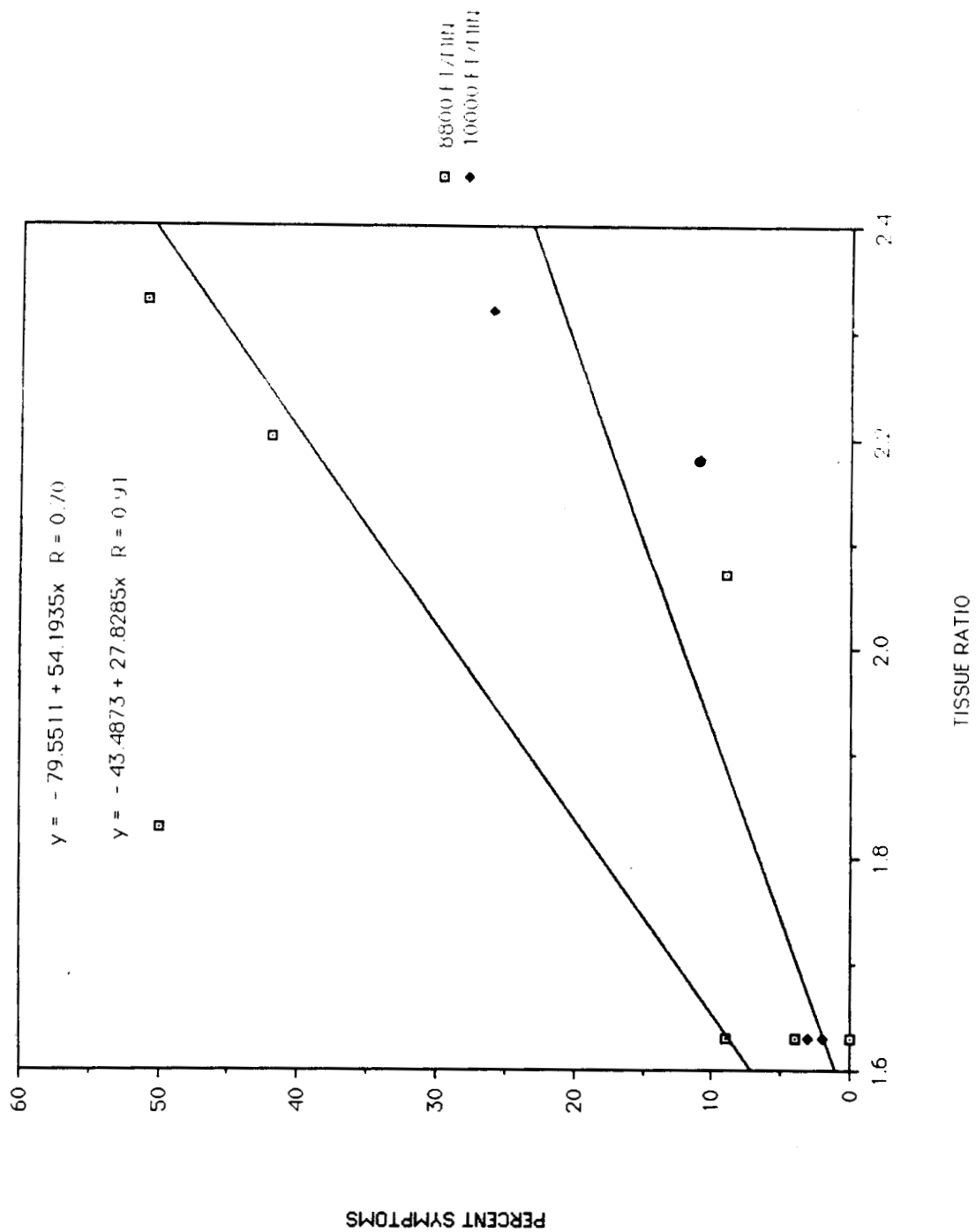
Figure 20. - Incidence of symptoms at 8800 ft/min and 10,000 ft/min in exercising subjects.

$y = -75.9832 + 57.065x \quad R = 0.73$

$y = -395.7176 + 182.3625x \quad R = 0.75$

10-20000 FT/MIN

>20000 FT/MIN

TISSUE RATIO

PERCENT SYMPTOMS
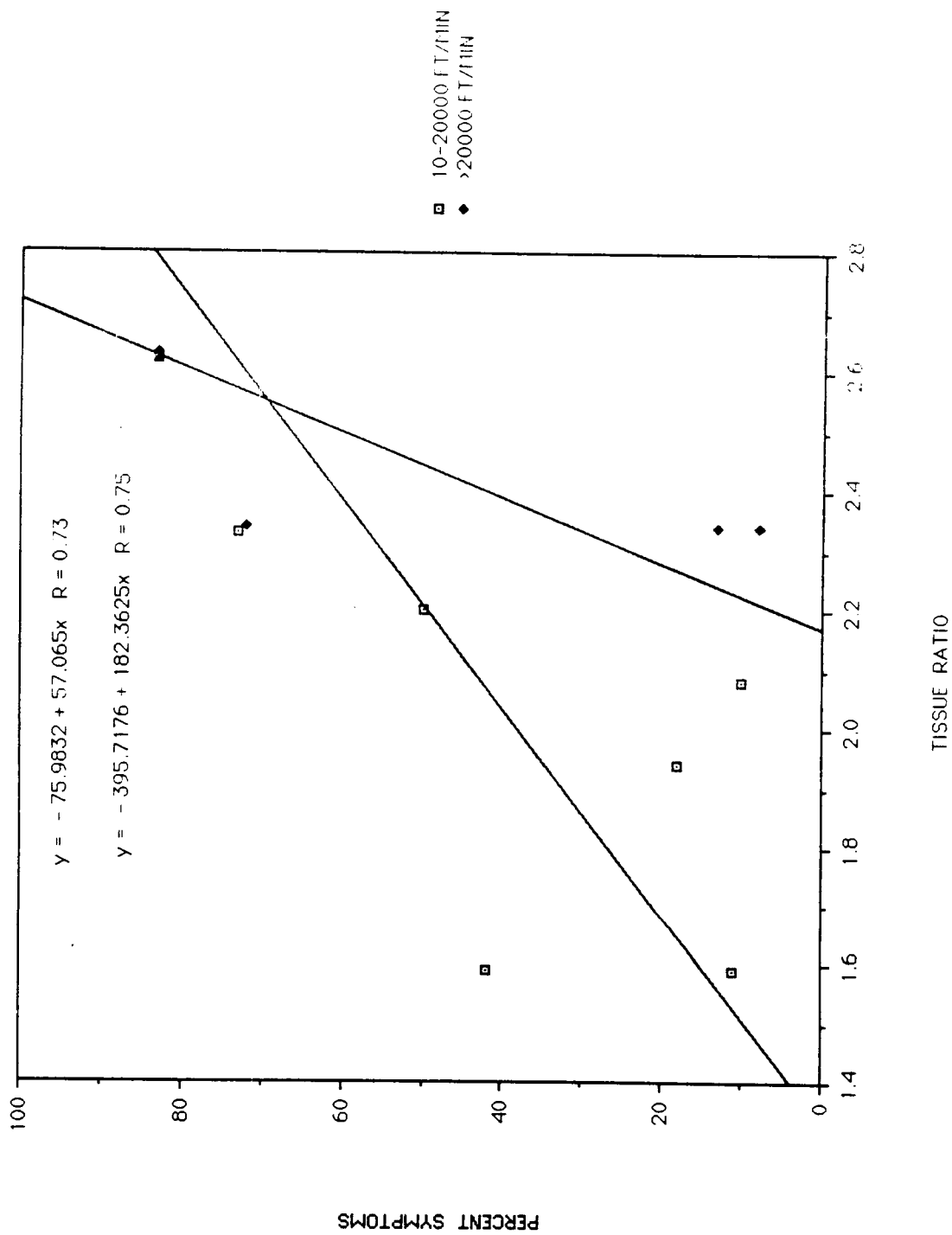
Figure 21. - Incidence of symptoms at rates between 10,000 ft/min to 20,000 ft/min and above 20,000 ft/min in exercising subjects.
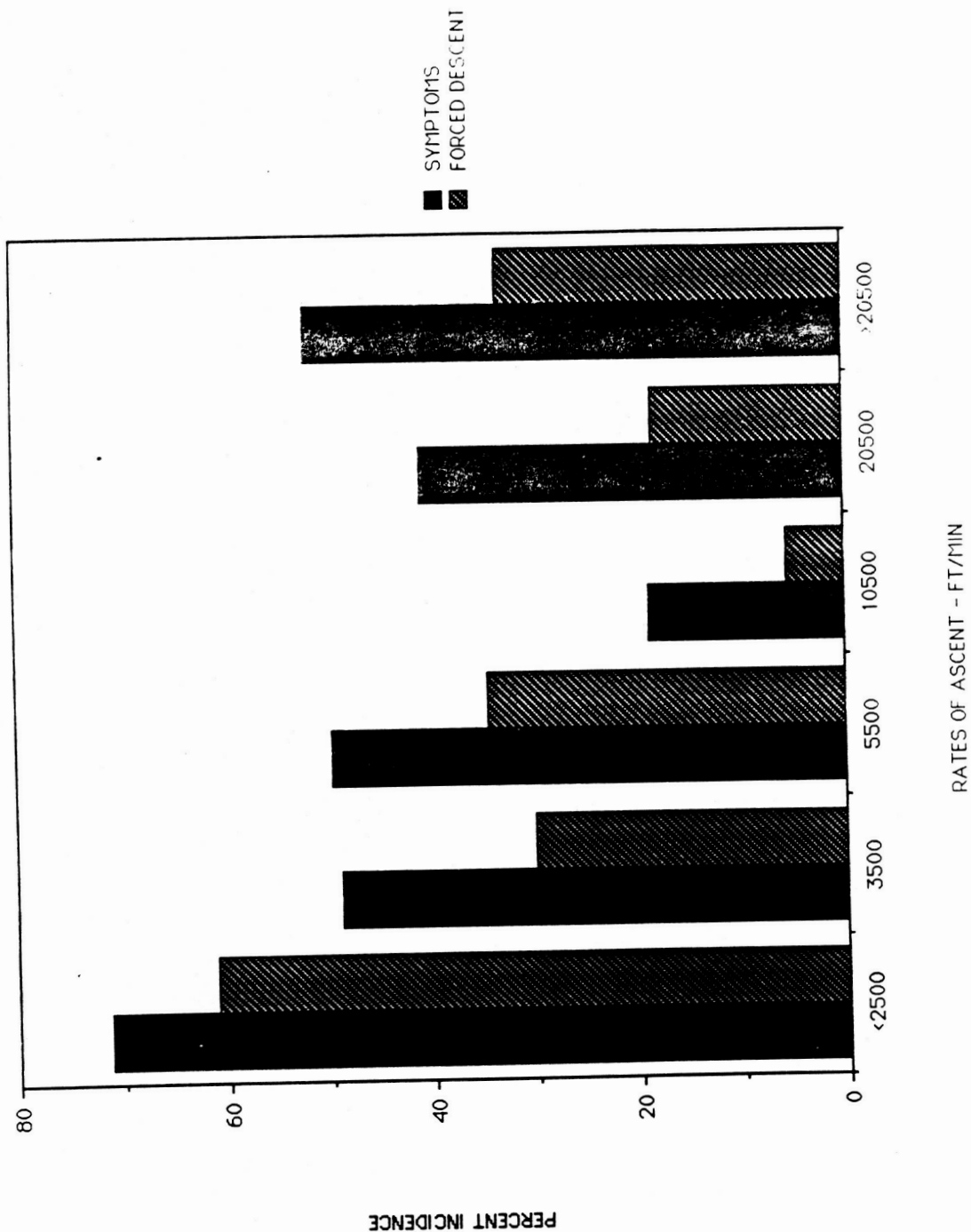
Figure 22. - Distribution of DCS under various ascent rates in subjects exercising at altitude.

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APPENDIX A: METHOD OF CALCULATING TISSUE RATIO

Tissue ratio (TR) is a measure of the supersaturation of body tissues with inert gas, especially nitrogen. In its simplified form, it is calculated as below (8):

$$\text{Tissue ratio} = \frac{\text{Final tissue pN2 (abs)}}{\text{Ambient pressure (abs)}} \ldots \qquad (1)$$

where pN2 is the partial pressure of nitrogen. Thus, at ground level ambient pressure of 14.7 psia, body tissues are taken to be in equilibrium with the ambient nitrogen partial pressure of 11.6 psia to yield a TR of 0.78 (11.6/14.7). This expression does not take into account alveolar partial pressure of nitrogen in order to avoid complex calculations.

During prebreathe, nitrogen elimination is determined by the theoretical 360-minute half-time tissue constant in the expression:

$$P_t = P_0 + (P_a - P_0)(1 - e^{-kt}) \ldots \qquad (2)$$

where P_t is the partial pressure of nitrogen after exposure for t minutes, P_0 is the initial partial pressure of nitrogen, P_a is the ambient pressure, e is the base of natural logarithm, and k is the tissue nitrogen partial pressure rate constant.

The tissue partial pressure rate constant is given by the expression:

$$k = (\ln 2) / t_{1/2} \ldots \qquad \ldots \qquad (3)$$

where $t_{1/2}$ is the tissue nitrogen partial pressure half-time (360 minutes, in this case). Various TR's given in this report were calculated based on the above equations using a computer program developed by this laboratory (15).

APPENDIX B : DATABASE ON ASCENT RATES COMPILED FOR REPORT

Altitude - feet (1)	Number of man-flights (2)	Time at altitude -hours (3)	Denitro-genation -hours (4)	Exercise frequency / hour (5)	Ascent rate ft/min (6)	Percent Symptom (7)	FD (8)	Ref. no. (9)
10000	7	6.0	0	12	5000	0	0	15
11500	30	6.0	0	12	5000	0	0	24
	6	6.0	0	12	5000	0	0	24
	11	6.0	0	12	5000	0	0	15
	20	6.0	0	12	5000	0	0	15
13000	14	6.0	0	12	5000	0	0	49
14000	17	2.0	0	12	3000	0	0	51
15000	31	6.0	0	6	5000	3	3	63
16500	16	6.0	0	12	5000	0	0	15
	30	6.0	0	12	5000	3	3	23
	32	6.0	0	12	5000	3	3	15
	32	6.0	0	12	5000	3	3	15
18000	36	12.0	0	4	18000	42	11	20
	73	12.0	0	4	18000	11	8	21
20000	1813	0.5	0	12	10000	–	0	65
23000	117	1.0	0	12	3000	8	1	35
25000	14	3.0	0	20	5000	43	14	29
	128	2.0	0	12	4000	10	2	39
	128	2.0	0	6	3000	12	2	35
	17	2.0	0	6	3000	0	0	51
26000	65	0.4	0	–	3000	2	0	64
	71	0.4	0	20	3000	17	1	64
	14	2.0	0	6	3000	36	21	51
27000	35	2.0	0	4	10500	26	–	2
	15	2.0	0	6	3000	47	33	51
	93	2.0	0	4	3000	9	1	35
	35	2.0	0.5	4	10500	11	–	2
	22	2.5	1.5	24	11500	18	5	22
	36	9.0	2.0	4	8800	50	39	3
	31	2.0	3.0	4	10500	3	–	2
	137	2.0	3.0	4	10500	2	–	2

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
27000	29	4.0	3.0	4	8800	4	0	52
(contd..)	53	4.0	3.0	4	8800	0	0	52
	32	9.0	3.0	4	8800	9	-	3
28000	80	0.4	0	-	3000	1	0	64
	17	2.0	0	-	3000	6	6	51
	17	2.0	0	-	3000	12	0	51
	65	0.4	0	20	3000	12	12	64
	18	2.0	0	6	3000	33	28	51
	17	2.0	0	6	3000	53	41	51
	19	2.0	0	6	3000	42	32	51
30000	92	0.4	0	-	3000	4	0	64
	14	8.0	1.0	-	5000	57	-	48
	111	1.5	0	24	3300	54	14	16
	14	3.0	0	20	5000	100	57	29
	53	1.5	0	24	3300	59	16	42
	122	0.4	0	20	3000	18	12	64
	24	2.0	0	20	5000	92	63	60
	111	1.5	0	12	3300	49	9	16
	61	1.5	0	12	3300	50	13	43
	135	2.0	0	12	4000	-	16	39
	135	2.0	0	4	3000	-	19	37
	24	2.0	1.0	12	5000	75	46	60
	14	8.0	1.0	4	5000	86	-	48
	11	3.0	3.5	12	5000	36	0	15
	23	4.0	3.5	12	5000	30	4	15
	28	6.0	4.0	12	5000	21	0	15
	19	6.0	6.0	12	3000	5	0	67
	19	6.0	6.0	12	3000	16	0	67
	8	6.0	8.0	12	3000	0	0	67
33000	100	2.0	0	-	3000	18	5	35
	100	2.0	0	-	3000	-	6	37
	134	1.5	0	12	3200	67	33	43
	28	3.0	0	12	3200	100	93	20
	143	2.0	0	4	3000	-	25	37
35000	73	2.0	0	-	2300	40	22	30
	264	2.0	0	-	2300	50	23	30
	118	2.0	0	-	1100	51	13	30
	3744	2.0	0	-	1100	36	18	30
	143	3.0	0	-	1100	55	18	30
	14	3.0	0	-	5000	36	21	29
	27	3.0	0	-	5000	48	26	27
	27	3.0	0	-	5000	33	30	27
	429	2.0	0	-	3000	-	16	37
	14	3.0	0	20	5000	100	86	29

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	36	1.5	0	12	2800	72	40	43
	72	3.0	0	20	5000	100	95	28
35000 (contd..)	27	3.0	0	20	5000	100	93	27
	9	3.0	0	12	3200	100	100	21
	14	3.0	0	8	5000	100	86	29
	14	3.0	0	4	5000	100	71	29
	14	3.0	0	4	5000	79	29	29
	147	3.0	0	4	1100	62	24	30
	149	2.0	0	4	3000	–	44	37
	27	3.0	1.0	20	5000	96	63	68
	14	3.0	1.0	20	5000	93	71	29
	63	2.0	1.0	24	3500	46	18	44
	86	1.5	1.0	24	3500	44	18	43
	73	3.0	1.0	20	5000	–	67	28
	27	3.0	2.0	20	5000	59	33	68
	14	3.0	2.0	20	5000	57	29	29
	27	3.0	2.0	20	5000	59	33	28
	75	3.0	2.0	20	5000	–	37	28
	12	3.0	2.0	20	17500	83	50	20
	12	3.0	2.0	20	27000	83	42	20
	12	3.0	2.0	20	52500	83	58	20
	37	3.0	3.0	4	8800	51	–	2
	11	3.0	3.0	4	11500	73	18	52
	12	3.0	3.0	4	52500	8	8	20
	22	3.0	3.0	4	35000	73	46	21
	8	3.0	3.0	4	35000	13	13	21
	12	3.0	4.0	20	5000	–	17	28
	7	3.0	8.0	20	5000	–	0	28
	26	3.0	3.5	4	8800	42	–	2
	33	3.0	4.0	4	8800	9	–	2
	10	3.0	3.5	4	11500	50	–	52
	10	3.0	4.0	4	11500	10	–	52
38000	33	2.0	0	–	3000	–	49	54
	76	2.0	0	–	4000	63	30	34
	32	4.0	0	–	5000	97	–	9
	223	2.0	0	–	4000	–	25	36
	223	2.0	0	–	3000	–	33	37
	204	2.0	0.3	–	4000	–	11	36
	145	2.0	0.5	–	4000	–	6	36
	180	2.0	0.8	–	4000	–	3	36
	87	2.0	0.8	–	4000	35	6	34
	4	2.0	1.3	–	5000	0	0	9
	8	2.0	2.0	–	5000	0	0	9
	17	2.0	4.0	–	5000	0	0	9
	33	2.0	2.0	–	3000	–	6	54
	23	2.0	0	4	5000	78	61	59

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	30	0.5	0	20	3000	100	100	54
	390	1.5	0	24	3200	87	–	43
	95	1.5	0	24	3200	91	74	16
	61	1.5	0	24	3100	87	65	43
	68	1.5	0	24	3100	74	37	43
38000	75	1.5	0	24	3100	83	55	43
(contd..)	75	1.5	0	12	3100	74	48	43
	75	1.5	0	12	3100	70	43	44
	157	1.5	0	12	3200	75	45	16
	167	1.5	0	12	3200	74	51	12
	35	1.5	0	6	5000	97	94	14
	45	1.5	0	6	5000	98	98	14
	57	2.0	0	6	1300	93	89	14
	19	2.0	0	6	1300	95	84	14
	14	2.0	0	6	1300	93	71	14
	13	2.0	0	6	1300	100	100	14
	61	1.5	0.5	12	4200	64	39	44
	61	1.5	1.0	12	4200	46	28	44
	45	1.5	0.5	6	5000	93	87	14
	57	2.0	0.5	6	1300	74	74	14
	35	1.5	1.0	6	5000	74	68	14
	45	1.5	1.0	6	5000	51	47	14
	19	2.0	1.0	6	1300	47	37	14
	14	2.0	1.0	6	1300	36	29	14
	13	2.0	1.0	6	1300	92	85	14
	23	2.0	1.0	4	5000	44	9	59
	61	2.0	2.0	12	4200	37	23	44
	45	1.5	2.0	6	5000	13	13	14
	19	2.0	2.0	6	1300	21	16	14

Percentage incidence of symptoms and forced descent were corrected to the nearest whole number. Incidence of DCS in references 59 and 60 were calculated after 2 hours at altitude.

1. Report No. NASA TM 100 472	2. Government Accession No.	3. Recipient's Catalog No.
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16. Abstract

The effect of different rates of ascent on the incidence of altitude decompression sickness (DCS) was analyzed by a retrospective study on 14,123 man-flights involving direct ascent up to 38,000 ft altitude. The data were classified on the basis of altitude attained, denitrogenation at ground level, duration of stay at altitude, rest or exercise while at altitude, frequency of exercise at altitude, and ascent rates. This database was further divided on the basis of ascent rates into different groups from 1000 ft/min up to 53,000 ft/min. The database was analyzed using multiple correlation and regression methods, and the results of the analysis reveal that ascent rates influence the incidence of DCS in combination with the various factors mentioned above. Rate of ascent was not a significant predictor of DCS and showed a low, but significant multiple correlation ($R=0.31$) with the above factors. Further, the effects of rates below 2500 ft/min are significantly different from that of rates above 2500 ft/min on the incidence of symptoms ($P=0.03$) and forced descent ($P=0.01$). At rates above 2500 ft/min and up to 53,000 ft/min, the effects of ascent rates are not significantly different ($P>0.05$) in the population examined while the effects of rates below 2500 ft/min are not clear.

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